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THESIS

OCEANOGRAPHIC INVESTIGATION OF THE
EAST GREENLAND POLAR FRONT
IN AUTUMN

by

William F. Perdue

March 1982

Thesis Advisor: R. G. Paquette

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Dense data sampling, both horizontally and vertically, have provided new insight into the time/space variability of the East Greenland Polar Front during late autumn. A core of warm Atlantic Intermediate Water (AIW) is frequently found pressed against the eastern edge of the front which is warmer than previously described and is often fragmented and full of finestructure. There is also finestructure present in the Polar Water in the form of lenses of anomalous water, generally warm in a cold matrix,

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which are formed by the turbulent entrainment of AIW at the front. There is a pronounced movement of AIW under the front which results in a warming of the waters found on the Greenland Shelf. This warm water has as its source AIW which has penetrated the lower portion of the front either some distance north of Fram Strait or along a part of the East Greenland Current or both. There is evidence that eddies or other mechanisms are involved in this process.

Oceanographic Investigation of the East Greenland Polar Front in Autumn

by

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Lieutenant, United States Navy
B.A., University of Texas, 1974

Submitted in partial fulfillment of the
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March 1982

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ABSTRACT

Dense data sampling, both horizontally and vertically, have provided new insight into the time/space variability of the East Greenland Polar Front during late autumn. A core of warm Atlantic Intermediate Water (AIW) is frequently found pressed against the eastward edge of the front which is warmer than previously described and is often fragmented and full of finestructure. There is also finestructure present in the Polar Water in the form of lenses of anomalous water, generally warm in a cold matrix, which are formed by the turbulent entrainment of AIW at the front. There is a pronounced movement of AIW under the front which results in a warming of the waters found on the Greenland Shelf. This warm water has as its source AIW which has penetrated the lower portion of the front either some distance north of Fram Strait or along a part of the East Greenland Current or both. There is evidence that eddies or other mechanisms are involved in this process.

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The author wishes to express sincere gratitude to Dr. R. G. Paquette and Dr. R. H. Bourke for their patience, support and guidence throughout the research and preparation of this thesis. Special thanks are also in order to Mike McDermet who provided helpful suggestions and support in the completion of drawings and figures. Lastly, without the special support and patience of my wife, Sonja, both during my absence from home during the cruise and during the long hours of preparation, this thesis would not have been possible.

I. INTRODUCTION

This thesis describes and analyzes some of the results of an oceanographic cruise to the marginal ice zone of the northwestern Greenland Sea in October to November of 1981 in which the author participated. The primary jectives were to:

- Observe the characteristics and vari ty of the front along the eastern boundary of th . Greenland Current.
- Search for mesoscale eddies in the frontal area.
- Investigate the recirculation of Atlantic Water into the East Greenland Current.

Aagaard and Coachman (1968a) list investigations in the area of interest for all seasons up to 1965 amidst a thorough review of the literature on the East Greenland Current. Up to the present, only three previous oceanographic cruises have occurred in the months of September to December. The first two (data were available from National Oceanographic Data Center archives) are the cruises of the icebreaker EDISTO in 1964 and 1965 which sampled with reversing bottles and used station spacings of approximately 35km along a line. Both of these cruises took place in August and

September. The stations which occurred in September are indicated in Figure 15. The third cruise, by the USCGC WESTWIND in September to October of 1979, was reported by Newton and Piper (1981). The data in the latter cruise were taken by a conductivity-temperature-depth recorder (CTD) and used station spacings of about 15km along a line. Additional information is available from the drift of the ice island Arlis II in 1964 to 1965 (Tripp and Kusunoki, 1967); also from several excursions of the British submarine SOVEREIGN under the ice carrying a recording sound velocimeter (Wadhams, Gill and Linden, 1979).

The present cruise was carried out with station spacings generally less than 10km in the region of the front. The Neil Brown CTD was programmed to sample about three times per meter. Thus it was possible to demonstrate the structure of the waters in considerable detail, showing complex and extensive finestructure and features interpretable as eddies or meanders. There are a number of samplings of the same sections at different times, thus demonstrating the variability with time.

The results presented in this thesis are based on the analysis of temperature and salinity fields. The analysis of density, dynamic heights and temperature-salinity curves are left for later work.

II. GENERAL OCEANOGRAPHY

A. BATHYMETRY

The bathymetry of the Greenland Sea (Figure 1) is marked by several major physiographic features. The 600km wide and 2600m deep Greenland-Spitsbergen passage, known as Fram Strait, forms the principal route for water exchange between the Arctic Ocean and the rest of the world ocean. A broad continental shelf extends southward along the east coast of Greenland with the shelf break at approximately the 400m isobath. In the region of Belgica Bank, the shelf reaches its widest extent of approximately 300km and then narrows rapidly to less than 100km at about 75°N. The shelf is marked by several depressions and a system of banks less than 200m in depth. The largest depression, Belgica Dyb, has a depth in excess of 400m.

A system of prominent ridges serves to define the limits of the Greenland Sea and divide it into two major basins. Extending from Greenland eastward to Jan Mayen at about 71°N, the Jan Mayen Fracture Zone forms a sill of the order of 1500m in depth and marks the southern extent of the

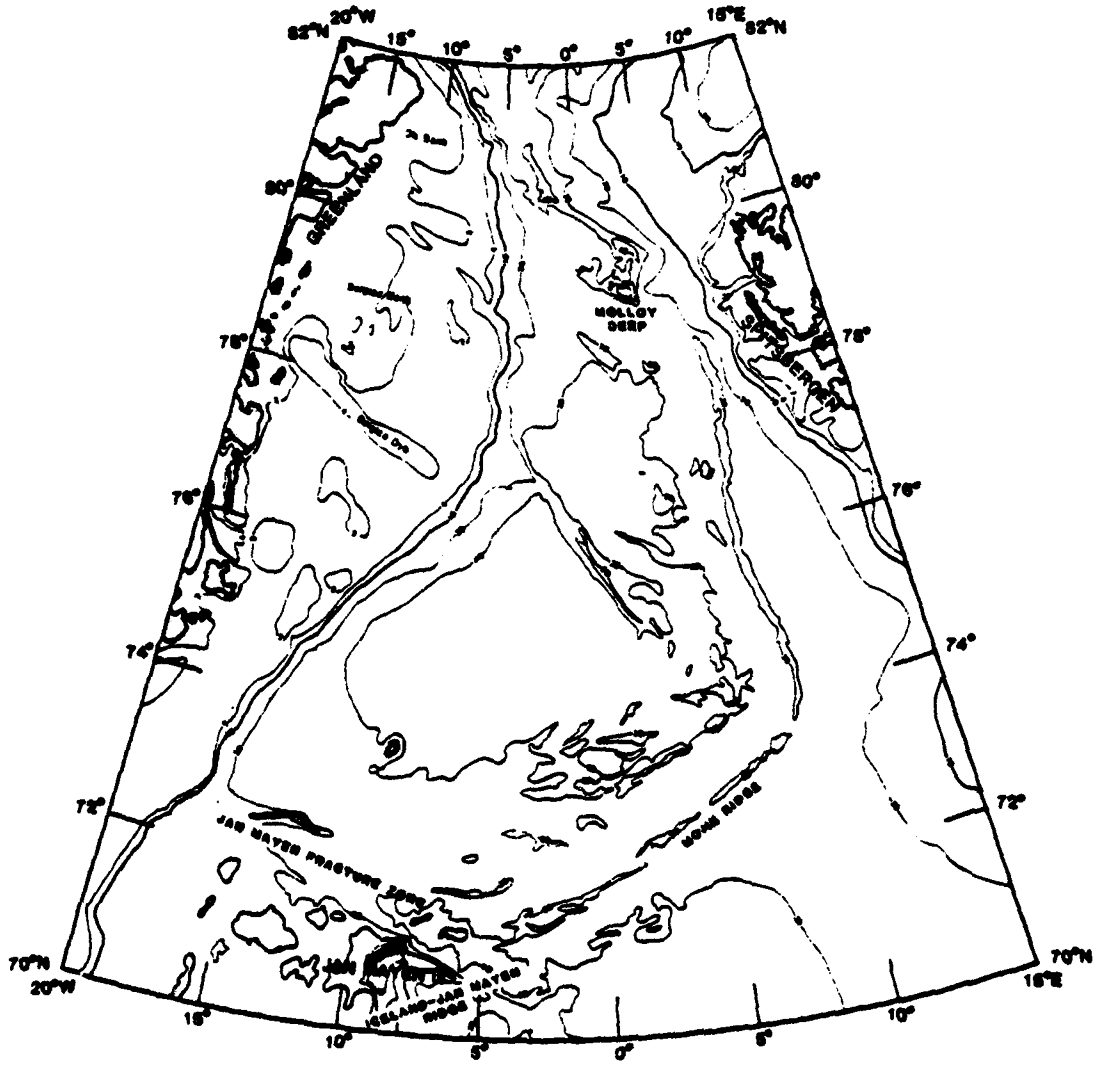

Figure 1. Bathymetry of the Greenland Sea. Adapted from the chart of Perry, Fleming, Cherkis, Feden and Vogt (1980). Bottom contours are in 100's of meters.

Greenland Sea. From Jan Mayen, a portion of the Mid-Atlantic Ridge known as the Mohn Ridge extends northeastward toward Spitsbergen. This ridge forms the logical oceanographic boundary between the eastern limit of the Greenland Sea and the Norwegian Sea to the south and east. The third important ridge lies northwest/southeast between Greenland and the Mohn Ridge from about 77°N, 5°W to 74°N, 5°E and separates the two basins of the Greenland Sea. The southern basin is the larger and deeper of the two, with depths of approximately 3800m. The northern basin is about 3200m in depth.

B. CIRCULATION

The surface circulation in the Greenland Sea is shown in Figure 2. The circulation is derived from a map given by Aagaard and Coachman (1968a). Added have been possible routes for the recirculation westward into the East Greenland Current of approximately $30 \times 10^{6}\ m^{3}s^{-1}$ of the water from the West Spitsbergen Current mentioned by the same authors. Also added is the western branch of the Norwegian-Atlantic Current along the Iceland-Jan Mayen Ridge inferred by Carmack and Aagaard (1973).

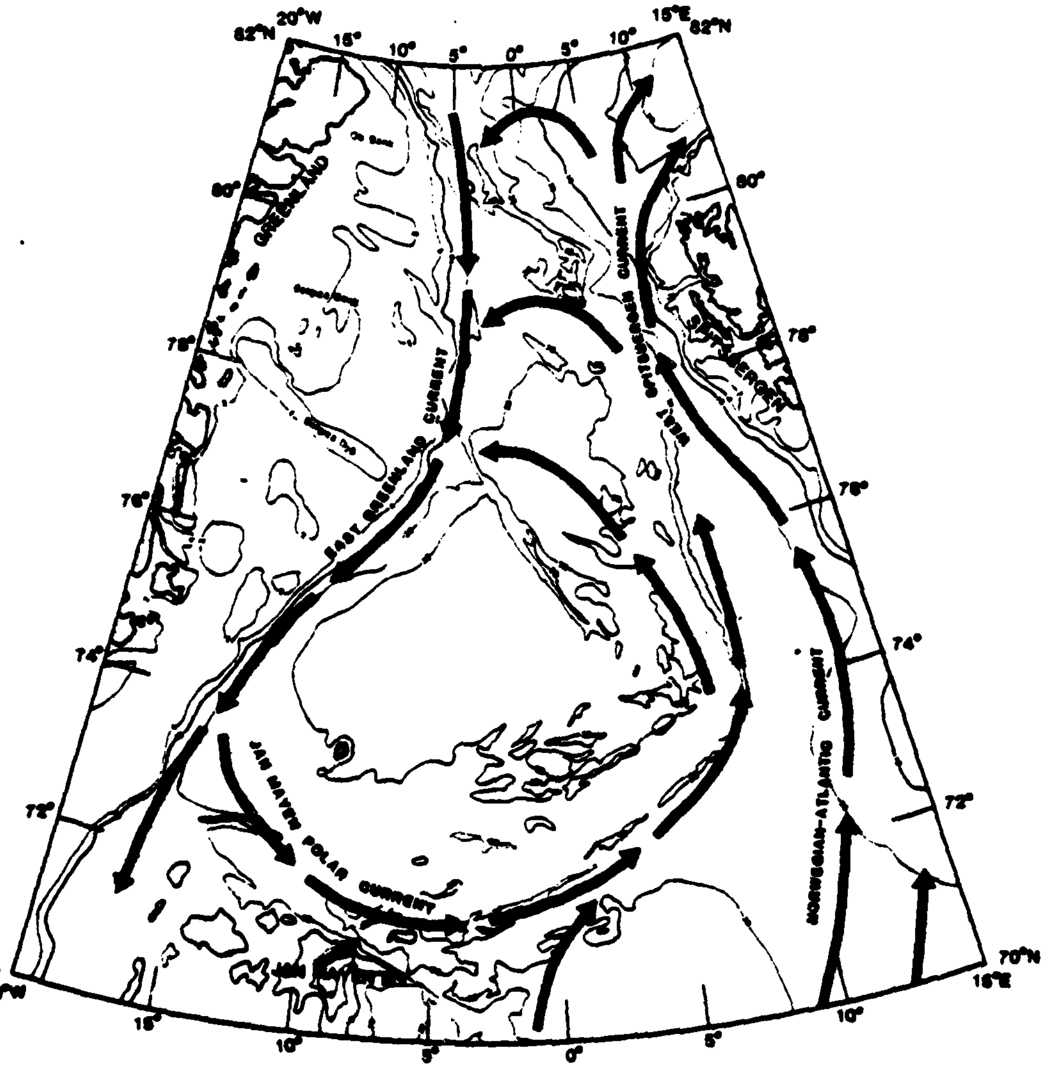

Figure 2. Surface circulation in the Greenland Sea.

C. WATER MASSES

Three water masses have been recognized historically within the East Greenland Current north of the Denmark Strait and in the Greenland Sea. Aagaard and Coachman (1968a) identified these as the Polar Water flowing out of the Arctic Ocean, the Atlantic Intermediate Water found in the eastern limits of the current, and the Deep Water which represents the majority of the water found in the Greenland Sea.

More recently, Swift and Aagaard (1981) expanded and modified the water mass terminology of the Greenland and Iceland Seas. In the area of the present study, their classification unnecessarily complicates the descriptions and the older nomenclature has been preferred here. Only Polar Water and Atlantic Intermediate Water are discussed below as Deep Water is generally associated with depths in excess of 800m and was seldom sampled during this cruise.

1. Polar Water (PW)

Polar Water is primarily confined to the continental margin of the Greenland coast and extends from the surface to a depth of approximately 150m. Originating in the Arctic

Ocean, PW flows out through the Greenland-Spitsbergen passage as part of the East Greenland Current. PW is characterized by low temperatures and low salinities. The temperatures vary from near freezing at the surface to 0°C at the bottom of the layer while the salinities form a strong halocline with values of 30.0 o/oo or less near the surface and a maximum value of 34.5 o/oo (Aagaard and Coachman, 1968a).

2. Atlantic Intermediate Water (AIW)

Atlantic Intermediate Water is a relatively warm, saline water water mass which is found east of the front. As defined by Aagaard and Coachman (1968a), the temperature of AIW is always greater that 0°C, with a temperature maximum normally present lying between 200 and 400m. The salinity of AIW has been defined as characteristically greater than 34.88 o/oo by the same authors.

On the western side of the front, there is a warm water mass with properties similar to AIW. The temperatures are greater than 0°C. However, the salinities of 34.5 o/oo to 34.9 o/oo appear to have somehow been diluted from the properties given above for AIW. Therefore, this water represents AIW which has mixed with cooler, usually less saline water such as PW. It is possible that this mixing has taken place in or north of Fram Strait or it may have occurred along the front.

D. EAST GREENLAND POLAR FRONT

Past studies have frequently referred to the front formed by the East Greenland Current as the Polar Front. Another front, also termed the Polar Front, exists along the eastern boundary of the Greenland Sea overlying the Mohn Ridge and another to the south and east of Spitsbergen. In order to distinguish between these fronts and to provide a more descriptive name, the terminology introduced by Wadhams, Gill, and Linden (1979) will be adopted and the more westerly of these fronts will be refered to as the East Greenland Polar Front.

The East Greenland Polar Front marks the eastern edge of the East Greenland Current, separating the cold, relatively fresh polar water flowing southward out of the Arctic Ocean from the warm, saline waters of Atlantic origin to the east. The front forms a boundary in which the isotherms, isohalines and isopycnals slope westward with depth to depths of about 200m or more. Aagaard and Coachman (1968b) arbitrarily chose the 0°C isotherm and 34.5 o/oo isohaline at 50m depth to mark the eastern limit of the front near the surface. In the descriptions below, the surface position of the front has been found by following the closely packed isotherms and isohalines as they approach the surface and extrapolating, if necessary. Where frontal slopes are given numerical values, it is the slopes of isotherms which are singled out.

There has been considerable variability in reports of the slope of the front. Aagaard and Coachman (1968b) reported a slope downward to the west exceeding $1m\text{-}km^{-1}$ over 120km or more at latitude 75°N. Based upon submarine crossings of the front between depths of 85 and 122m and at latitude 80°-30'N, Wadhams et al. (1979) calculated a slightly smaller slope of the order of 1 in 1200. Values reported by Newton and Piper (1981) show a much steeper slope of $3.3m\text{-}km^{-1}$ in the region of Belgica Dyb. Such variations in slope is not unexpected and can be due to differences in either position or time, as will be seen later. Values for the slope of the front from the present cruise varied from $1.5m\text{-}km^{-1}$ to $20m\text{-}km^{-1}$.

A significant feature which has been associated with the East Greenland Polar Front is the existence of subsurface cores of relatively cold water east of the front. Aagaard and Coachman (1968b) discussed three such cold patches found near the front at about 75°N, 78°N and 79°N between 30m and 75m in depth. The temperatures were less than 0°C and salinities were between 34.0 o/oo and 34.6 o/oo. They did not demonstrate that the apparent density anomaly persisted in spite of the corresponding salinity changes. Several explanations for the possible causes of such features were suggested by the same authors. These included detached eddies, quasi-stationary meanders and variations in the intensity of the Greenland Sea circulation.

Newton and Piper (1981) found another cold core near 79°N only a few miles from one of the cores discussed by Aagaard and Coachman (1968b). It is interesting that similar eddy-like structures have been reported in the same general area in the past. Gladfelter (1964) found one by temperature and salinity measurements; Vinje (1978) found one using buoy drifts and satellite imagery. Vinje (1978) also indicated that this eddy might be a semi-permanent, bottom steered eddy due to the presence of a circular depression (Molloy Deep) centered at 79°15'N, 3°E. This deep is about 2000m deeper than the surrounding bottom topography and about 60km in diameter. Wadhams et al. (1979) suggested that it is not clear whether all the eddies found in this area are really the same eddy, or whether the front in this region is simply a fertile generator of eddies.

Another phenomenon which may contribute to the formation of the cold core structures may be associated with the local variability in the position of the East Greenland Polar Front. Aagaard and Coachman (1968b) noted several examples of apparent lateral movement occurring within relatively short time periods. One case cited a movement of the order of 100km within a few days. Although they did not clarify the mechanism, they suggested that such a movement could leave behind cold patches of water to the east of the front or contribute to the formation of eddies.

Warm eddies also have been inferred in and west of the frontal zone by Wadhams et al. (1979). They interpreted fluctuatuions in sound velocity profiles found during transects through the front by a submarine at depths of 67 and 85m as warm regions.

One final phenomenon which may have some importance in relation to the East Greenland Polar Front is the indication of temporal variation in intensity of the flow of Polar Water (Aagaard and Coachman, 1968b). In previous data, pulsations in ice drift velocity of one to two week period have been noted, probably reflecting similar pulsations in the water flow. From current measurements taken during the drift of the ice island Arlis II in the East Greenland Current in 1965, there are indications that relatively large variations in the flow may cccur over time periods as short as a day (Tripp and Kusunoki, 1967). Pulsations in either the ice or the water velocity might be expected to cause variations in the nature of the front.

III. RESULTS

The position of the front, both its near-surface and most deeply submerged manifestations, and the varying positions of the ice edge are shown in relation to the station array in Figure 3. The ice edge shown in the figure is not synoptic, having been constructed from observations of the position of the ice taken at the time of each ice margin crossing and from helocopter observations near 75°N. Additional information concerning ice conditions at the time of the cruise is provided by weekly southern ice limit charts produced by the Naval Polar Oceanographic Center (NPOC) (Appendix C).

The location of the front depicted in Figure 3 was determined from nine temperature and salinity transects constructed from data acquired during the cruise. The transects are numbered in chronological order and indicated in Figure 4 and Figure 5 by the solid lines connecting stations.

The nature of the frontal region varies in complexity according to geographic area. A relatively simple structure

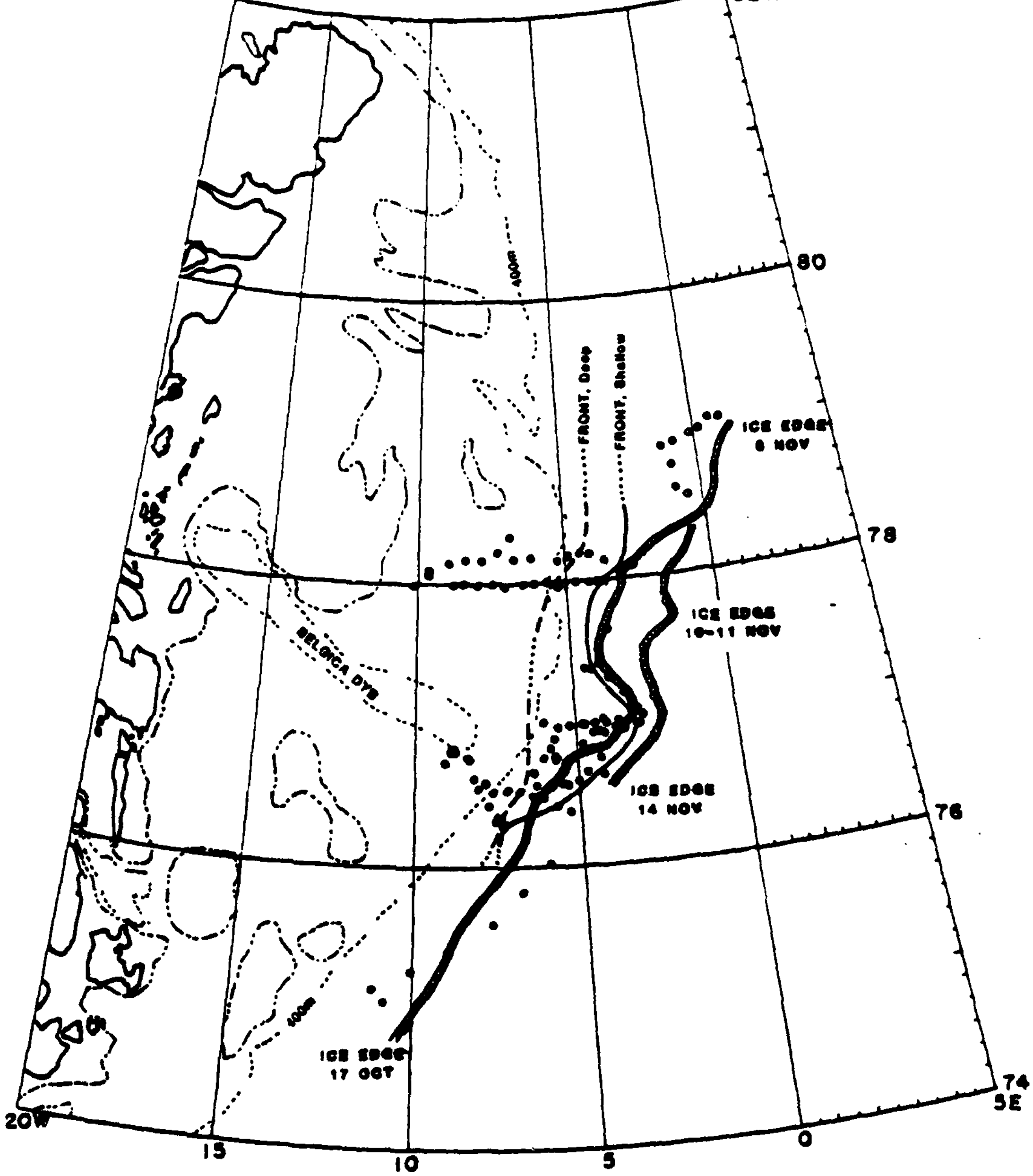

Figure 3. Distribution of oceanographic stations. The position of the ice edge is shown as well as the deep (broken line) and shallow (solid line) manifestatons of the front.

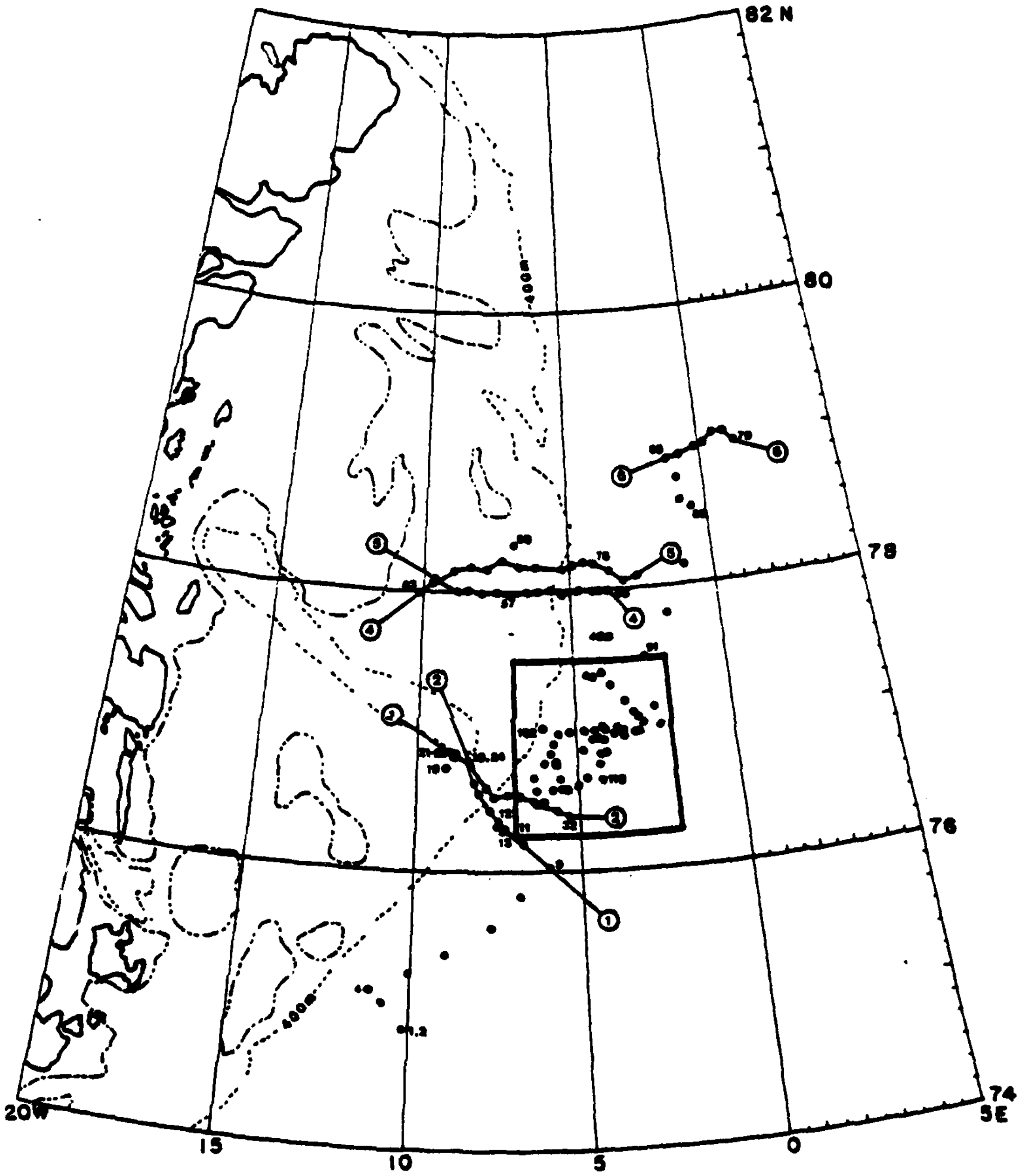

Figure 4. Distribution of salinity-temperature transects. Locations of transects are indicated by the solid lines connecting stations. The central portion of the study area (indicated by the box) is expanded in Figure 5.

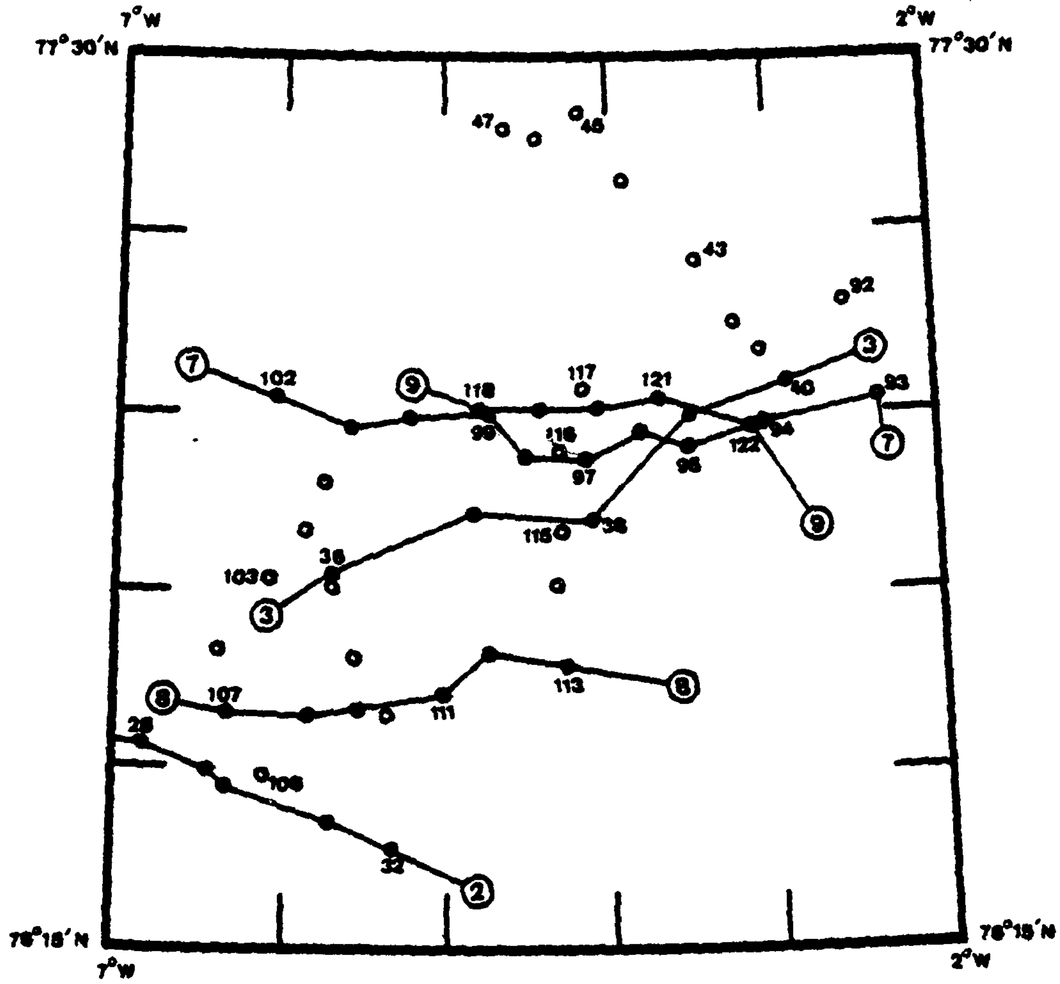

Figure 5. Distribution of salinity-temperature transects in the central area. Locations of transects are indicated by the solid lines connecting stations.

is seen in the northern transects, becoming somewhat more complex in the southern transects and very complex in the center of the study area. For this reason, the transects will be presented in that order.

Transect 6 represents a short transect in which only a small portion of the front was crossed. Because of this and several unusual features noted in the region, this transect will be presented separately.

A. NORTHERN TEMPERATURE-SALINITY TRANSECTS

The northern temperature-salinity transects were obtained near 78°N. These are Transects 4 and 5 of Figure 4.

1. Transect 4

Transect 4 (Figure 6) was constructed from data acquired from stations 50 through 62 while inbound onto the Greenland continental shelf. The stations were occupied over a 39 hour period and are therefore thought to be reasonably synoptic. XBT profiles 90, 91 and 95 were added to the transect in the region of the front in order to provide a more complete picture of the frontal structure near the surface.

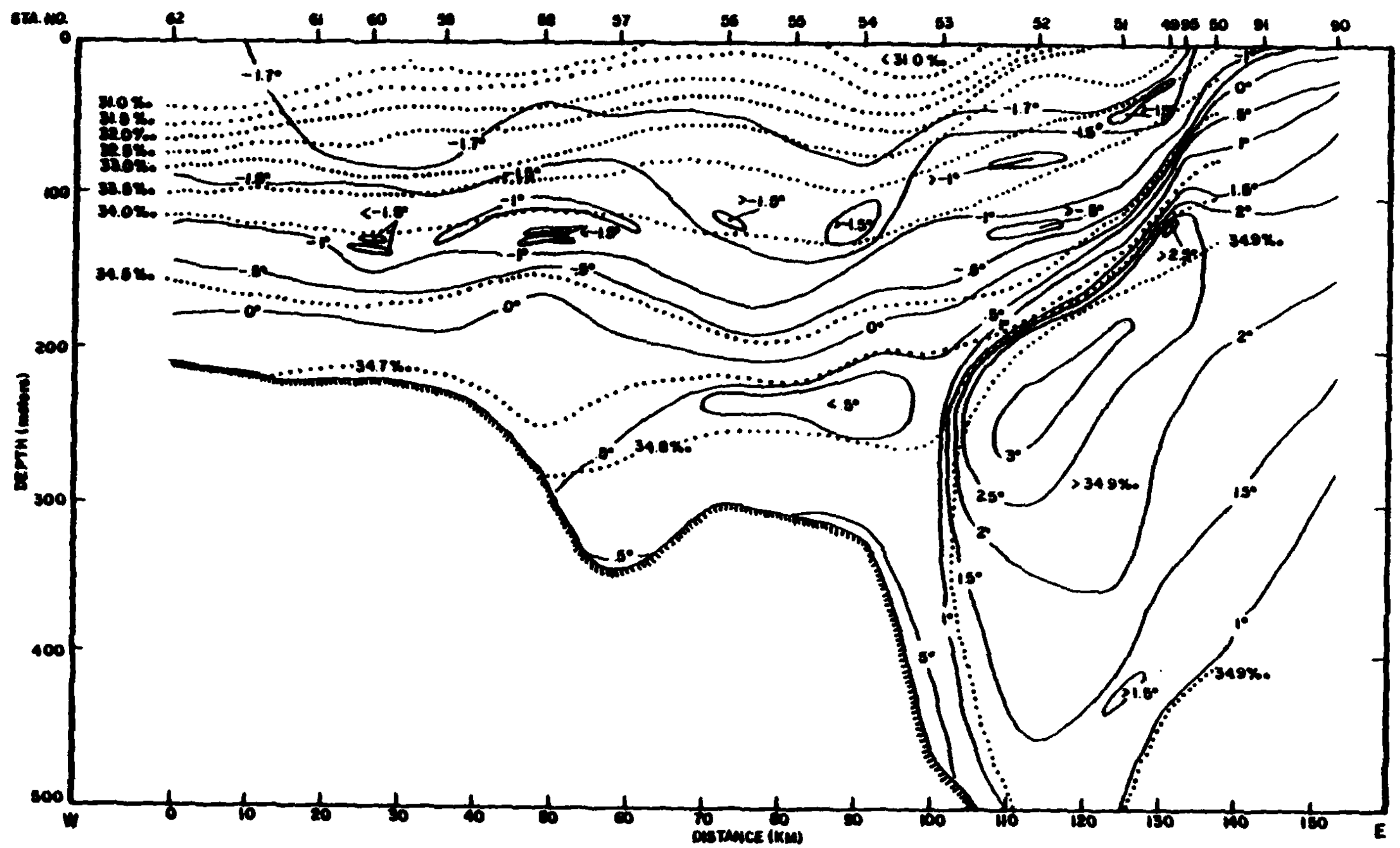

Figure 6. Temperature-Salinity Transect 4. Isotherms are indicated by the solid lines; isohalines by the broken lines. Stations 90, 91 and 95 were XBT drops.

The East Greenland Polar Front appears as an intense temperature front coincident with a strong salinity front lying between Stations 50 and 53. The isopleths of temperature and salinity slope steeply downward ($4.8m \cdot km^{-1}$) from near the surface to about 200m depth then turn sharply toward the bottom of the continental slope. The 27.6 $kg \cdot m^{-3}$ sigma-t surface, approximately in the middle of the sharpest horizontal gradient, slopes slightly less steeply and levels off at about 160m depth. This general characteristic of the isopycnals as compared to isotherms holds also in the other frontal transects described below. The lower portion of the front is close to the shelf break. This relationship is seen in other transects of the present cruise as well as in the historical data.

To the east of the front below 100m lies a large region of water which meets the definition of Atlantic Intermediate Water. A well defined core within the AIW with maximum temperature >3.0°C is present between 100 and 500m depth and between Stations 50 to 53. This core and associated water may represent a portion of the return flow of Atlantic waters discussed by Coachman and Aagaard (1974) and will be seen in other transects from the present cruise.

West of the front, a wedge shaped layer of Polar Water can be identified. Extending from the surface to approximately 180m, a strong halocline is evident with salinities increasing from <31.0 o/oo at the surface to about 34.5 o/oo in the region of the 0°C isotherm. Temperatures vary from 0°C at the bottom of the layer to values near freezing (<-1.7°C) near the surface. Numerous parcels of anomalously warm or cold water form temperature inversions and finestructure in the lower part of the PW.

Below the 0°C isotherm, temperatures rise slightly to +0.5°C at the bottom. These temperatures coupled with salinities of 34.6 o/oo to >34.8 o/oo, indicate diluted AIW.

The nature of the front near the surface can be related to some degree to the advance or retreat of the ice margin. In this transect, the ice edge lies between XBT profiles 90 and 91, about 15km seaward of the shallow portion of the front. The isopleths of temperature and salinity appear to have been stretched eastward, creating a gentler slope in the front near the surface. This could be caused by an advance of the ice edge eastward with consequent cooling of near-surface water. That such an extension of the ice edge did occur may be seen from ice-limit charts produced by the Naval Polar Oceanographic Center (Figures 21 and 22, Appendix C). An advance in the ice margin of about 35km in the two week period from 13 to 27 October 1981 occurred near 78°N.

2. Transect 5

Data acquired from stations occupied in the transect lying just north of Transect 4 were used to construct Transect 5 (Figure 7). Although the stations were occupied over a period of 5 days, the stations in the region of the front were occupied over a 15 hour period and may be regarded as synoptic. Stations 74 through 78 represent the region of the front about 10.5 days later than that seen in Transect 4. Again the front appears as an intense and steep temperature-salinity front with isopleths sloping downward toward the shelf at about $3.8 m\text{-}km^{-1}$.

The ice edge in this transect was located between Stations 77 and 78, coincident with the shallow portion of the front. The slope of the front near the surface becomes gentler and displays the same eastward stretching of the isopleths seen in the previous transect. The ice margin in this case had advanced another 35km from 27 October to 10 November.

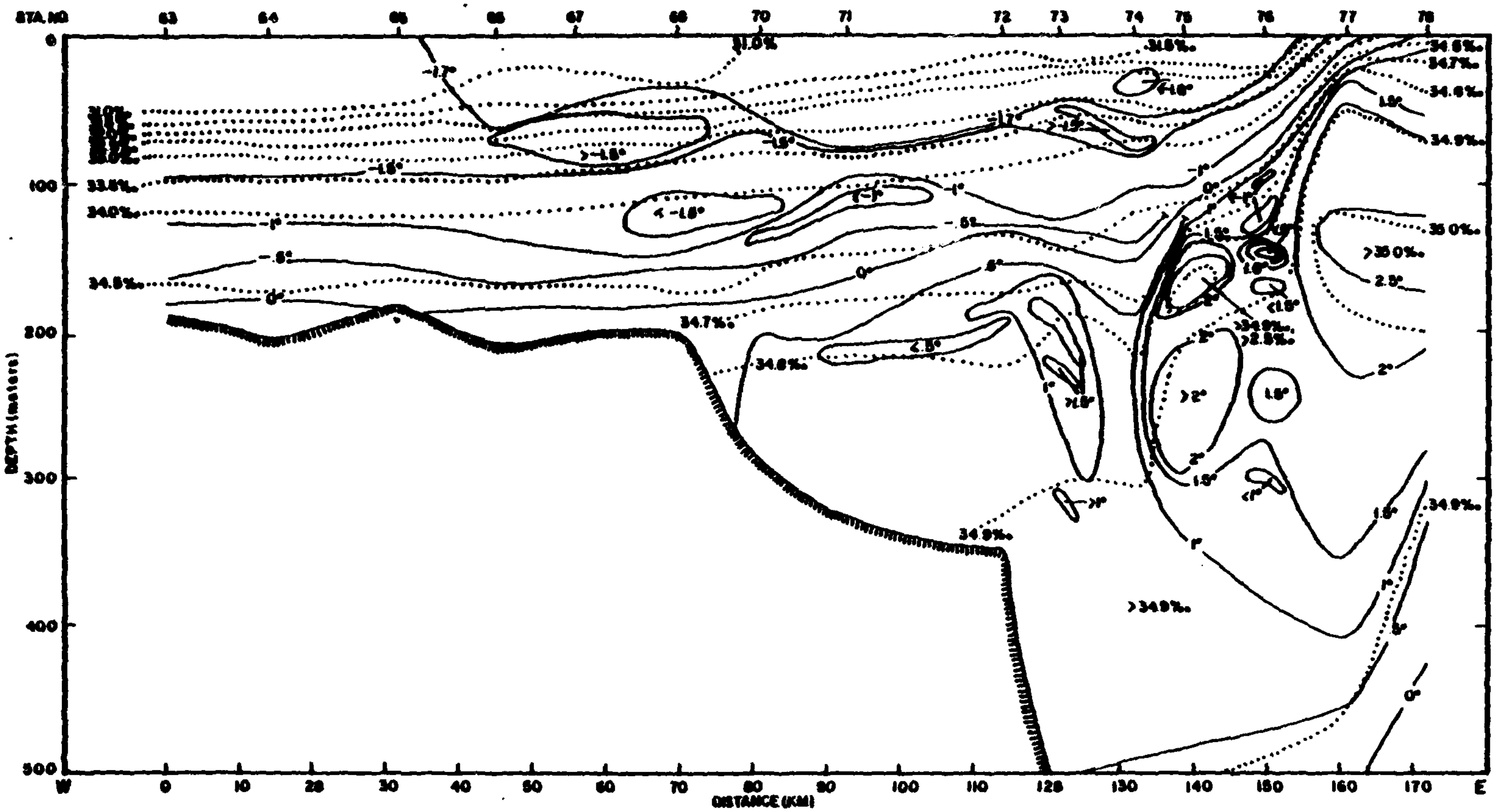

Figure 7. Temperature-Salinity Transect 5. Isotherms and isohalines are as indicated as in Figure 6.

A notable contrast between this and the previously discussed representation of the front is in the warm core in the AIW east of the front. In 10.5 days, the structure of the core altered considerably. Instead of being a single well-defined core, the AIW is distributed among several cores or parcels extending from about 50m in depth to 500m or more. The maximum temperature anywhere in the region of the AIW is near 2.5°C, 0.5°C cooler than in the earlier transect and the maximum salinity is slightly higher, 35.03 o/oo versus 34.96 o/oo. This probably is a region of turbulent mixing, a condition which seems to be common along the front. Perhaps included in the same turbulent process is the parcel of warm water near Station 73 and 200m depth, to the west of the front. This suggests a tendency for AIW to mix across the front in large parcels at depths of about 200m. Similar behaviors will be seen in more southerly transects.

The PW in this transect is similar in properties and thickness to that in Transect 4. The diluted AIW found below the 0°C isotherm also is similar except for the warm parcel at Station 73 mentioned above.

B. SOUTHERN TEMPERATURE-SALINITY TRANSECTS

The southern temperature-salinity transects represent transects of the front obtained in the region of Belgica Dyb. These are Transects 1 and 2 of Figure 4.

1. Transect 1

Transect 1 (Figure 8) represents the most southerly transect of the East Greenland Polar Front during the cruise. The stations were occupied over a 62 hour period while inbound on the shelf in the region of Belgica Dyb. The temperature front in this transect is the most intense seen during the cruise. The isotherms slope very steeply down from the surface to about 150m with a slope of about $20m\text{-}km^{-1}$. In this case, the isohalines slope much less steeply. The bottom portion of the front appears to overlie the region of the shelf break as in previous transects.

Again one sees the Atlantic Intermediate Water broken up into secondary cores or parcels. The tendency of the AIW to penetrate the lower portion of the front is more pronounced than in Transect 5. A large parcel of warm, undiluted AIW is found at Station 11 and 200m depth near the base of the front. Additionally, warm, undiluted AIW can be seen along the surface of the shelf and a particularly warm,

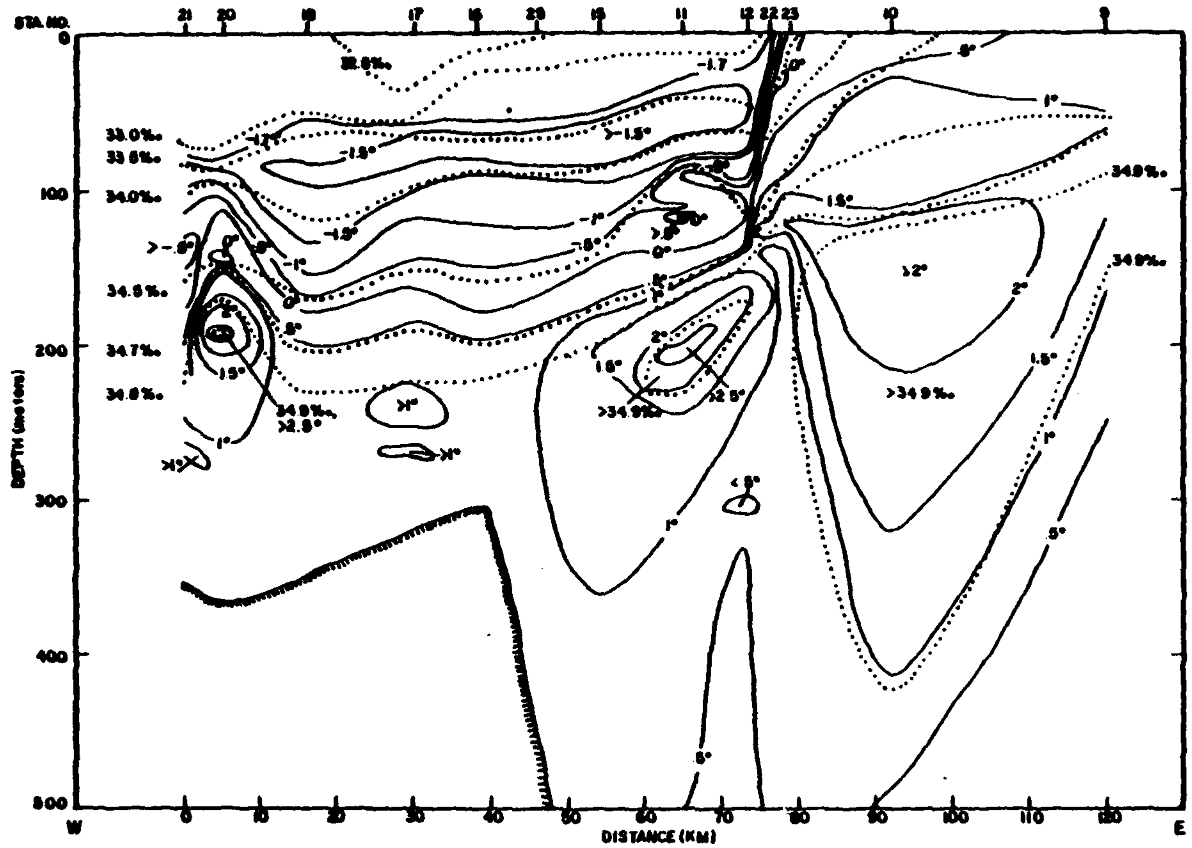

Figure 8. Temperature-Salinity Transect 1. Isotherms and isohalines are indicated as in Figure 6. Stations 22, 23 and 29 were XBT drops.

essentially unaltered parcel is visible as far as in Station 20. This represents a well-defined intrusion of the AIW across or below the front. This penetration of AIW landward is more pronounced than in Transect 4 possibly because of the flow of water into Belgica Dyb proposed by Newton and Piper (1981).

2. Transect 2

Cross section 2 (Figure 9) was constructed from data obtained while headed eastward from Belgica Dyb. Again the data are considered to be approximately synoptic, having been acquired over a 24 hour period. This transect provides a representation of the East Greenland Polar Front eight days after that of Transect 1.

The front remains clearly defined. It is less intense than in Transect 1 and less steep, with a slope of approximately $8.5m\text{-}km^{-1}$, as compared to the slope of $20m\text{-}km^{-1}$ eight days previously. The bottom of the front extends to about 200m depth, approximately 50m deeper than Transect 1. Additionally, the lower portion of the front overlies the upper continental slope as before. There is some evidence of the flattening of the front near the surface which has been associated with the advance of the ice

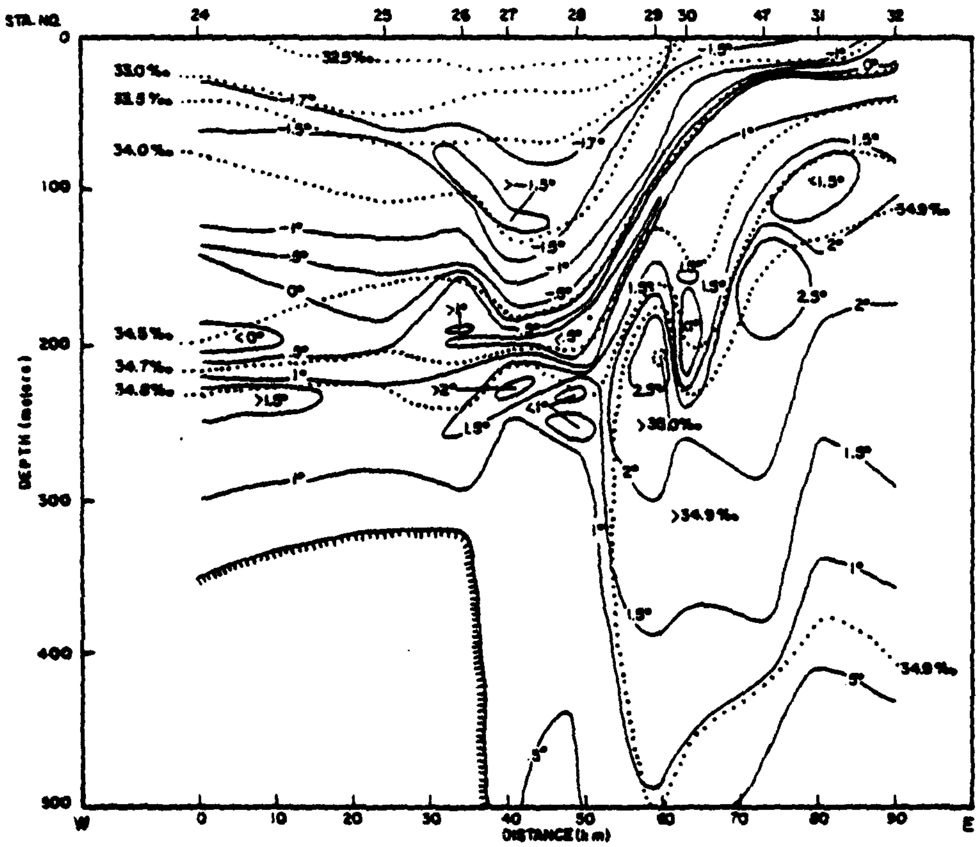

Figure 9. Temperature-Salinity Transect 2. Isotherms and isohalines are indicated as in Figure 6. Station 47 was an XBT drop.

margin in previous discussions. However, the ice edge is found near Station 30 in this case, which is behind the surface manifestation of the front. A possible explanation for this may be an advance in the ice margin which subsequently retreats and leaves a layer of PW to the east. From the ice charts in Appendix C, it appears that such an event may have occurred. From 13 to 20 October, the ice edge in the region of Transect No. 2 (near 76°-30'N) grew about 10km eastward. The chart of 27 October shows the ice margin to have returned westward to the position of 13 October.

C. CENTRAL TEMPERATURE-SALINITY TRANSECTS

Transects 3 and 7-9 represent transects through the central part of the study area (Figure 5) and provide an interesting view of the variability of the front over small scales of time and space.

1. Transect 3

The transect represented by Transect 3 (Figure 10) was completed relatively early in the cruise on 26 October during a 14 hour period. Its western end is about 35km seaward of the shelf break, which prevents seeing the way in which the front approaches the shelf. Station spacings were somewhat larger than in the other transects (15-20km) and some of the fine detail seen elsewhere may have been missed.

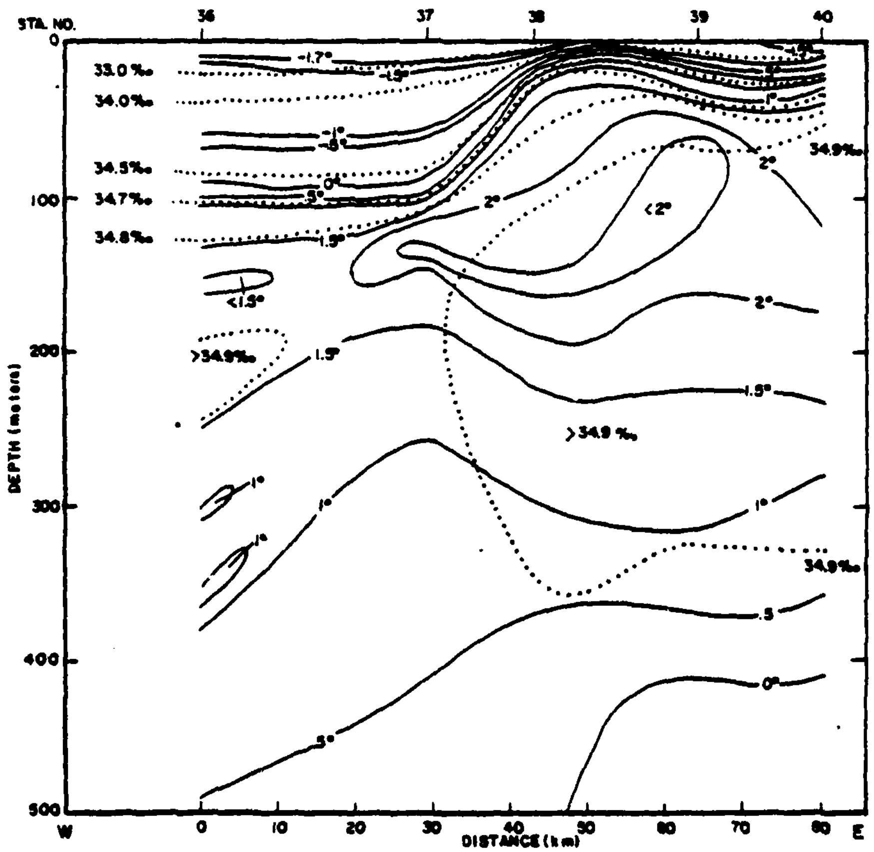

Figure 10. Temperature-Salirity Transect 3. Isotherms and isohalines are indicated as in Figure 6.

There is a relatively sharp slope in the isopleths of about $5.2m\text{-}km^{-1}$ between Stations 37 and 38. The near-surface portion of the front stretches eastward, similar to what has been seen in other transects. The ice edge was located near Station 39 and had advanced about 25km over a period from 20 to 27 October. As seen from earlier discussion, this advance may be responsible for the apparent spreading of the front to the east. Additionally, the front flattens out abruptly at 100m depth and extends westward from station 37. This may be a breaching of the lower portion of the front as occurred in Figures 8 and 9. However, the unusually shallow depth at which this occurs and the general downward trend of the deeper isotherms near Station 36 suggest that a deeper manifestation of the front may have existed further to the west.

Just east of the front, but considerably shallower than before, the characteristic warm core of AIW is seen with the maximum temperature now reduced to about 2°C. Below the front, temperatures remain above 0°C, also corresponding to AIW, except for a small region below 400m between Stations 38 to 40 which is, by definition, Greenland Sea Deep Water. Salinities in the western part of the transect are slightly lower than the values defined for AIW. However, one large area in the eastern part with salinities greater than 34.9 o/oo and a smaller area at Station 36 qualify as AIW.

2. Transects 7 through 9

Transects 7, 8 and 9 (Figures 11, 12 and 13) represent three transects of the East Greenland Polar Front accomplished over a period of less than four days from 11 - 15 November. It is particularly interesting to note the close proximity of Cross Transects 7 and 9 (Figure 5). Stations 99 and 107, and Stations 94 and 113 should be superimposed in comparing the two transects.

The slope of the front in all three transects is relatively gentle with values ranging from $1.5 m\text{-}km^{-1}$ to $2.3 m\text{-}km^{-1}$. Again, one sees the eastward spreading of the near surface portion of the front which appears to be associated with the 40km advance of the ice margin in this region from 26 October to 15 November (Figure 3). The deep end of the front is not present in any of the three transects.

Perhaps the most striking differences noted in Transects 7 through 9 is in the variability of the Atlantic

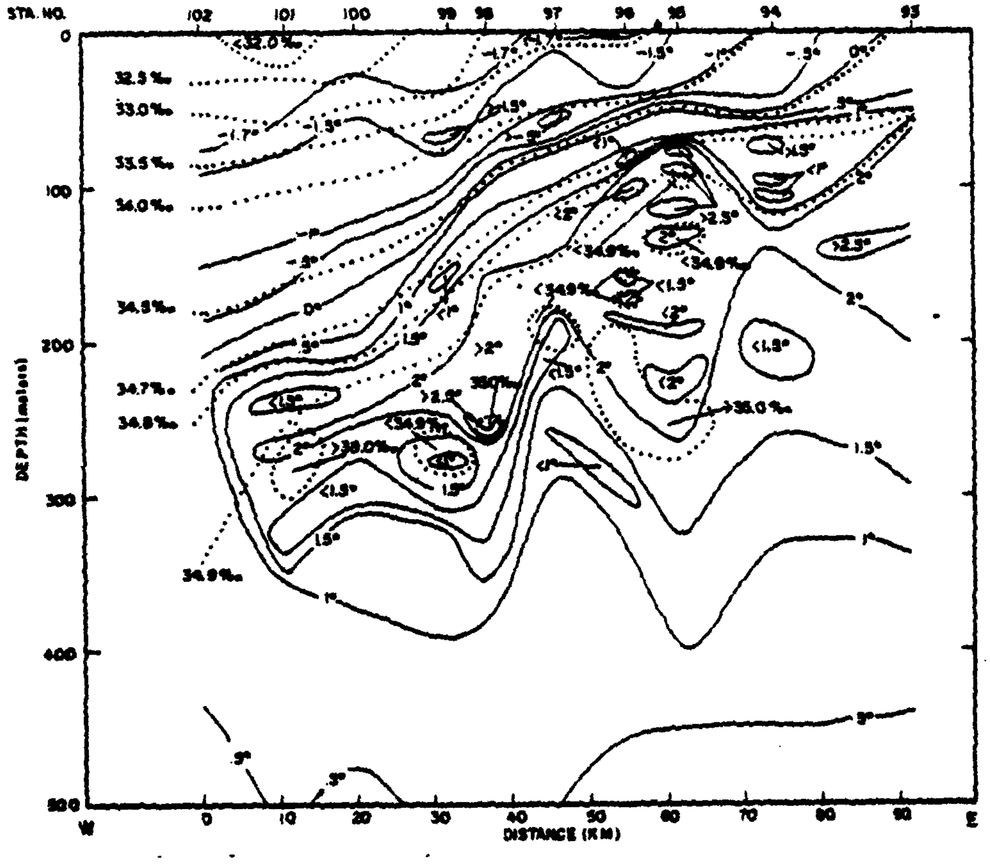

Figure 11. Temperature-Salinity Transect 7. Isotherms and isohalines are indicated as in Figure 6.

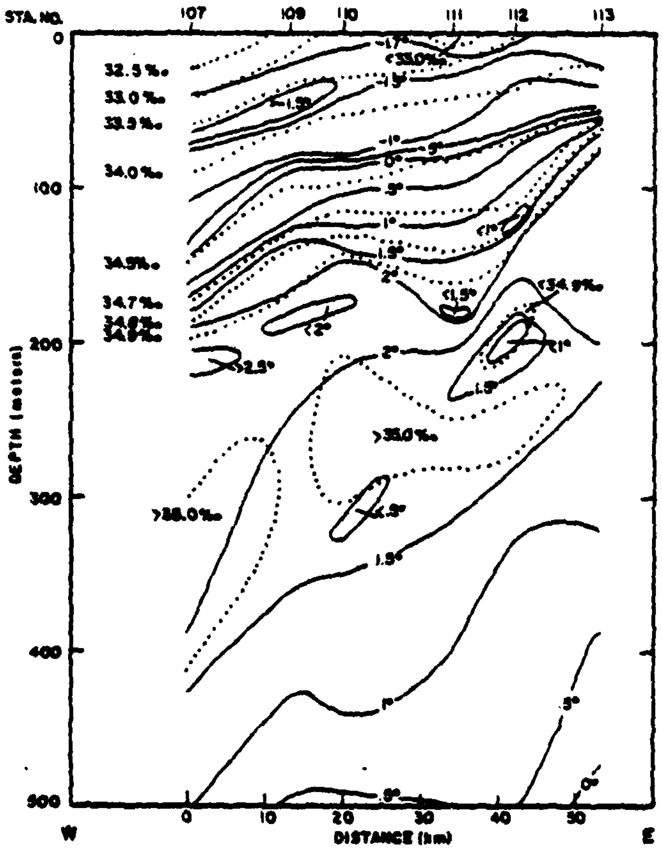

Figure 12. Temperature-Salinity Transect 8. Isotherms and isohalines are indicated as in Figure 6.

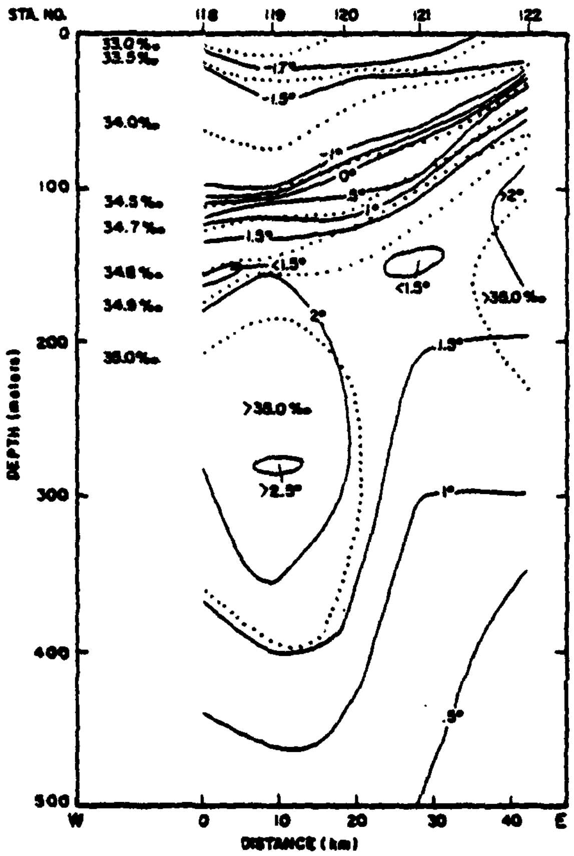

Figure 13. Temperature-Salinity Transect 9. Isotherms and isohalines are indicated as in Figure 6.

Intermediate Water. In Transect 7, the warm AIW east of the front contains much finestructure suggesting turbulent mixing of an intensity not previously seen. In contrast, Transect 9, only 3.5 days later than Transect 7, has a well defined core of warm AIW, scarely fragmented at all. Likewise, Transect 8, displaced only a short distance southward, shows little fragmentation in the AIW.

D. TRANSECT 6

Transect 6 (Figure 14) represents the most northerly transect accomplished during the cruise. Due to the relatively short distance covered by this transect, the crossing of the East Greenland Polar Front was not completed. Evidently, the transect is near the eastern (surface) end of the front and a thin layer of Polar Water extends eastward beyond Station 79, probably as a result of an 80km advance in the ice margin from 3 to 10 November. AIW is present in nearly all the volume beneath the PW. There is also an intervening thin layer of diluted AIW. AIW extends to 500m depth and more. Particularly notable is the prominent dome in the isotherms at Station 81 suggesting a submerged cold-core eddy.

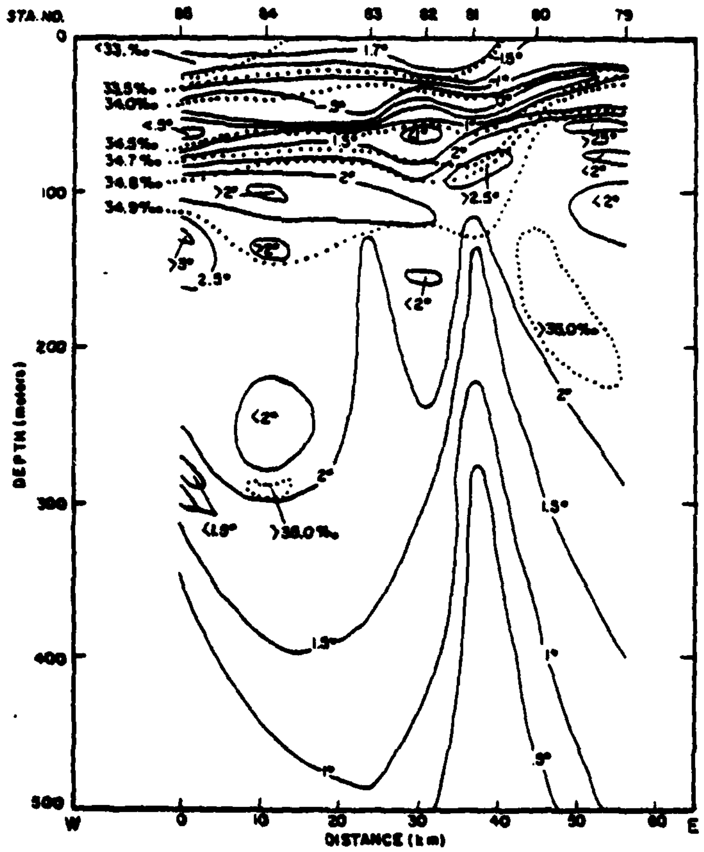

Figure 14. Temperature-Salinity Transect 6. Isotherms and isohalines are indicated as in Figure 6.

IV. DISCUSSION

We have seen the northern portion of the East Greenland Polar Front as a sharp, steep boundary between warm, saline Atlantic Intermediate Water on the east and cold, more dilute Polar Water underlain by a cooled layer of slightly diluted AIW on the west. The front consistently lies over the upper continental slope. Relatively warm AIW is close against the front in the depth range 200 to 400m. This warm water appears to be concentrated here in one core or a number of smaller filaments or parcels. However, there may be a continuity of the warm parts of this water with similar water to the east.

The high temperatures and high salinities found in the AIW adjacent to the front are indicative of a relatively direct connection with the Atlantic waters in the West Spitsbergen Current. There can be little doubt that this water is part of the recirculating water from the West Spitsbergen Current mentioned by Coachman and Aagaard (1974). It would be interesting to know if the warm AIW observed during this cruise has come more or less directly from the east or if it was injected at a more northerly point and flowed southward along the front. In two transects (Figures 6 and 8), there seems to be no well-defined continuity of the warmest AIW to the east. In other transects, the lack of continuity is not demonstrated, particularly if one conceives of the water arriving in the form of parcels or filaments which give the appearance of discontinuity. However, in all transects of the present cruise, AIW of intermediate temperature obviously continues eastward, to what distance it cannot be determined. Thus, the question of the more or less direct flow of warm AIW from the east cannot be answered with the present data.

Some insight into conditions farther to the east than the limits of the present survey may be had from the EDISTO data. The positons of two sets of temperature, salinity and density transects are indicated by the solid lines connecting stations in Figure 15.

In Transect A (Figures 16) temperatures of greater than 3°C are seen at the surface, but they are too dilute for AIW. Below approximately 90m, temperatures up to above 1.5°C have salinities high enough to be called AIW. The AIW with this degree of warmth is located against the front,

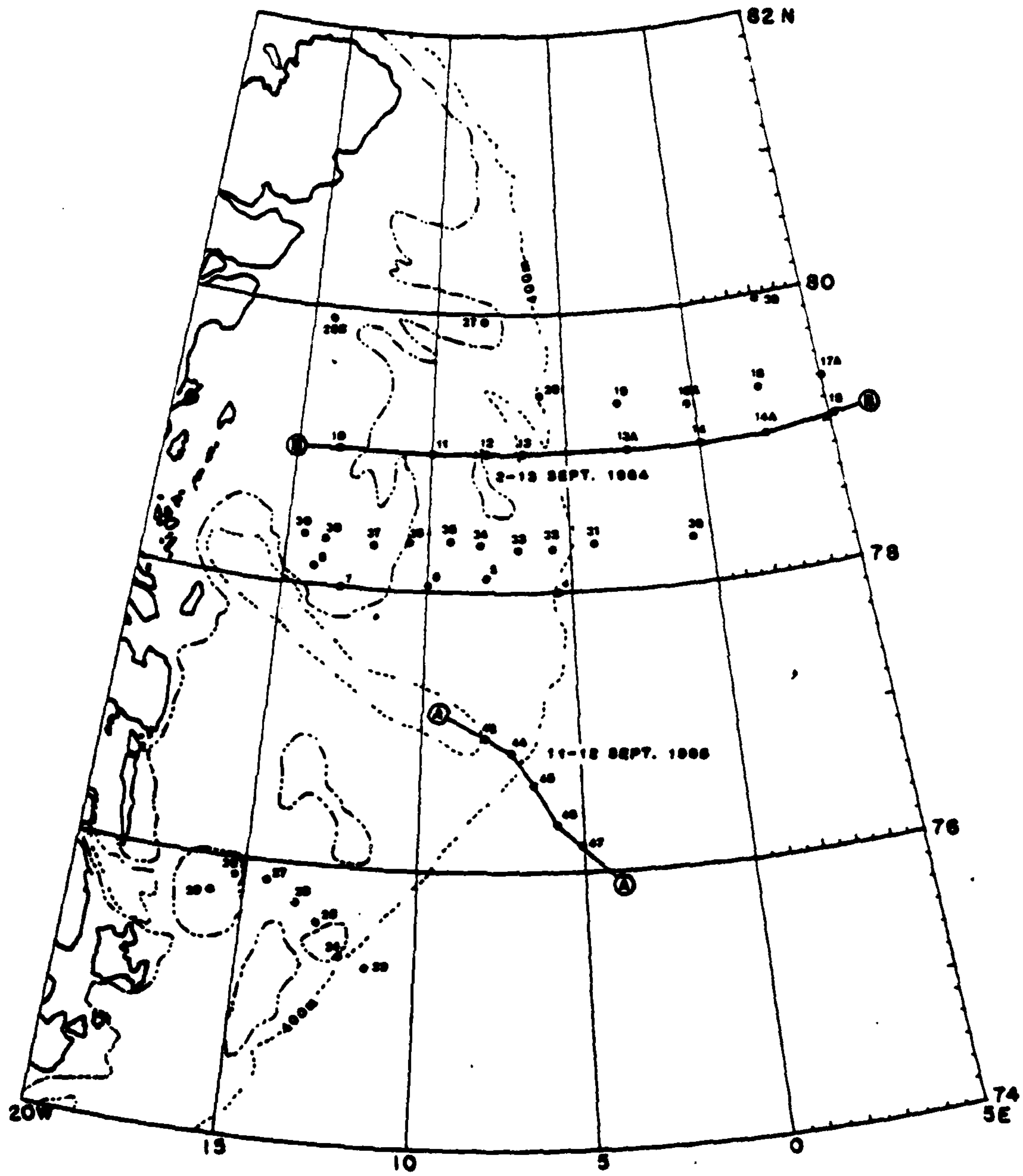

Figure 15. Distribution of oceanographic stations of the icebreaker EDISTO in September 1964 and 1965. Locations of transects are indicated by the solid lines connecting stations.

typically like the corresponding waters in 1981. Although this data is from September, the maximum temperatures are lower than 1981. The lower temperature in this year may be due to year-to-year variation. The transect extends only as far eastward as Transects 1 and 2 and therefore, does not provide much insight into conditions to the east. The maximum temperatures lie along isopycnals 27.9-28.0, which rise rapidly toward the east. This suggests a continuity with water farther to the east near or at the surface.

Transect B (Figures 17-19) extends approximately 60km farther eastward than Transect 6. Temperatures in the AIW are similar to the values seen in the present data. In contrast to Transect A, the warmth in the AIW (salinity ≥ 34.88 o/oo) does not appear to extend to the surface, but is held deeper than about 100m by a superficial layer of decreased density. The parcel of water warmer than 2.5°C on the right near 100m depth is approximately on the 35.0 o/oo isohaline. Temperatures decrease with depth to 500m but all of the deeper water to the east of the 275km mark may be classified as AIW. This extension of warm AIW to the east suggests that there is a continuous supply of this water from that direction. The previously mentioned parcel of

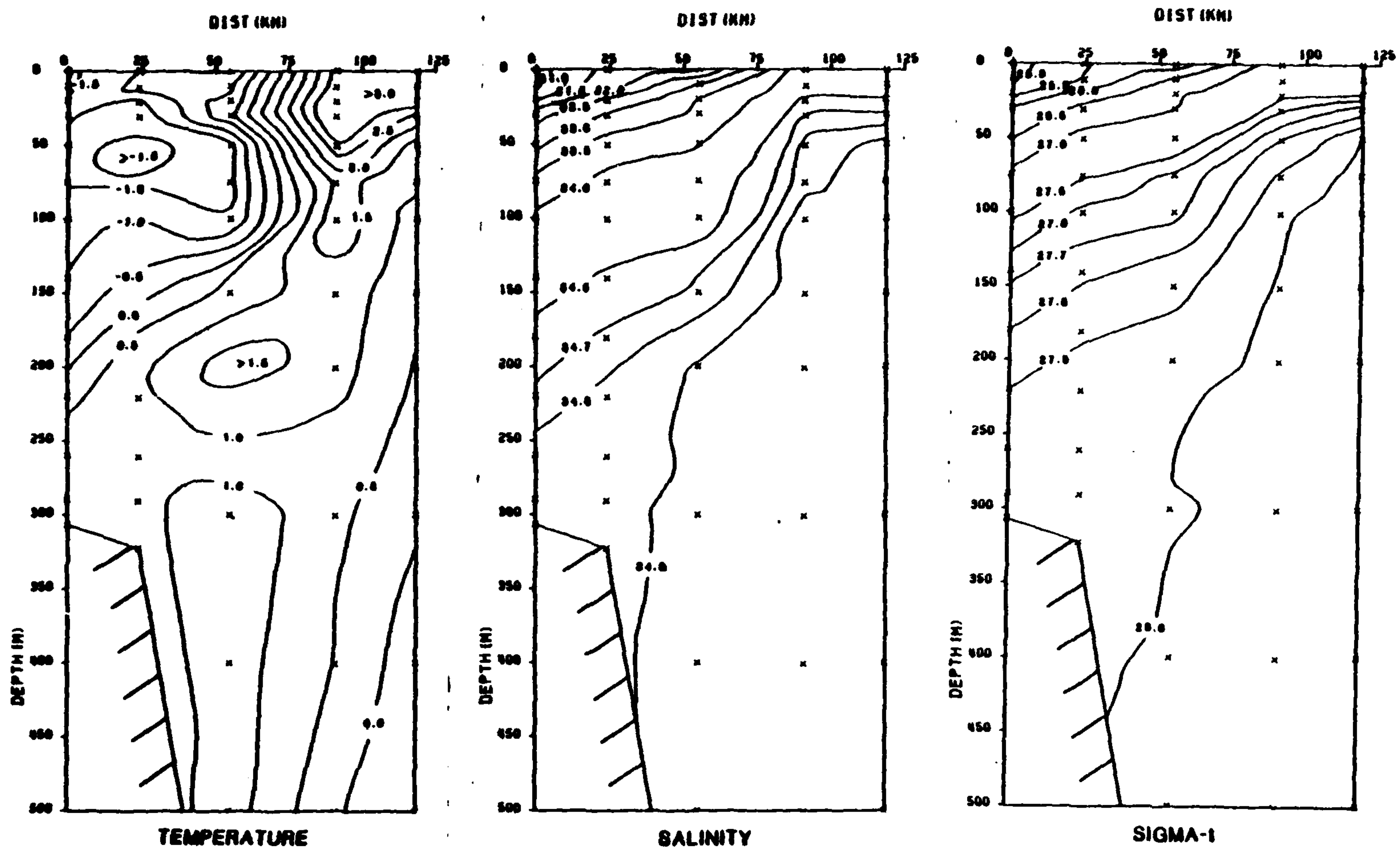

Figure 16. Transect A. Temperatures (^{o}C); Salinities (o/oo); Sigma-t ($kg{-}m^{-3}$).

water >2.5°C in the eastern portion of the transect suggests that the warmest AIW may arrive as parcels or filaments carried in the westward flow. Other warm parcels may have been missed by the large station spacings, approximately 60km.

In the present data, the finestructure visible in the Polar Water layer west of the front is less pronounced than in the AIW. Wadhams, Gill, and Linden (1979) also observed that the amplitudes of the fluctuations in sound velocity transects were greater on the warm side of the front in the AIW. The majority of the finestructure in the PW is made up of warm-in-cold parcels of the order of 15m in thickness and 10km in diameter. These may be seen in Figures 6, 8 and 9 lying bove approximately 130m depth. The fact that they are mostly warm-in-cold suggests that the parcels are propagating from the warm frontal zone. Since this is a region of high velocity shear, it is likely that these parcels have at some point been torn out cf the frontal zone by shear-induced turbulence. This same mechanism may account for some of the fragmentation seen in the AIW near the front.

Large concentrated parcels of AIW are found upon the shelf and propagating shoreward beneath the front

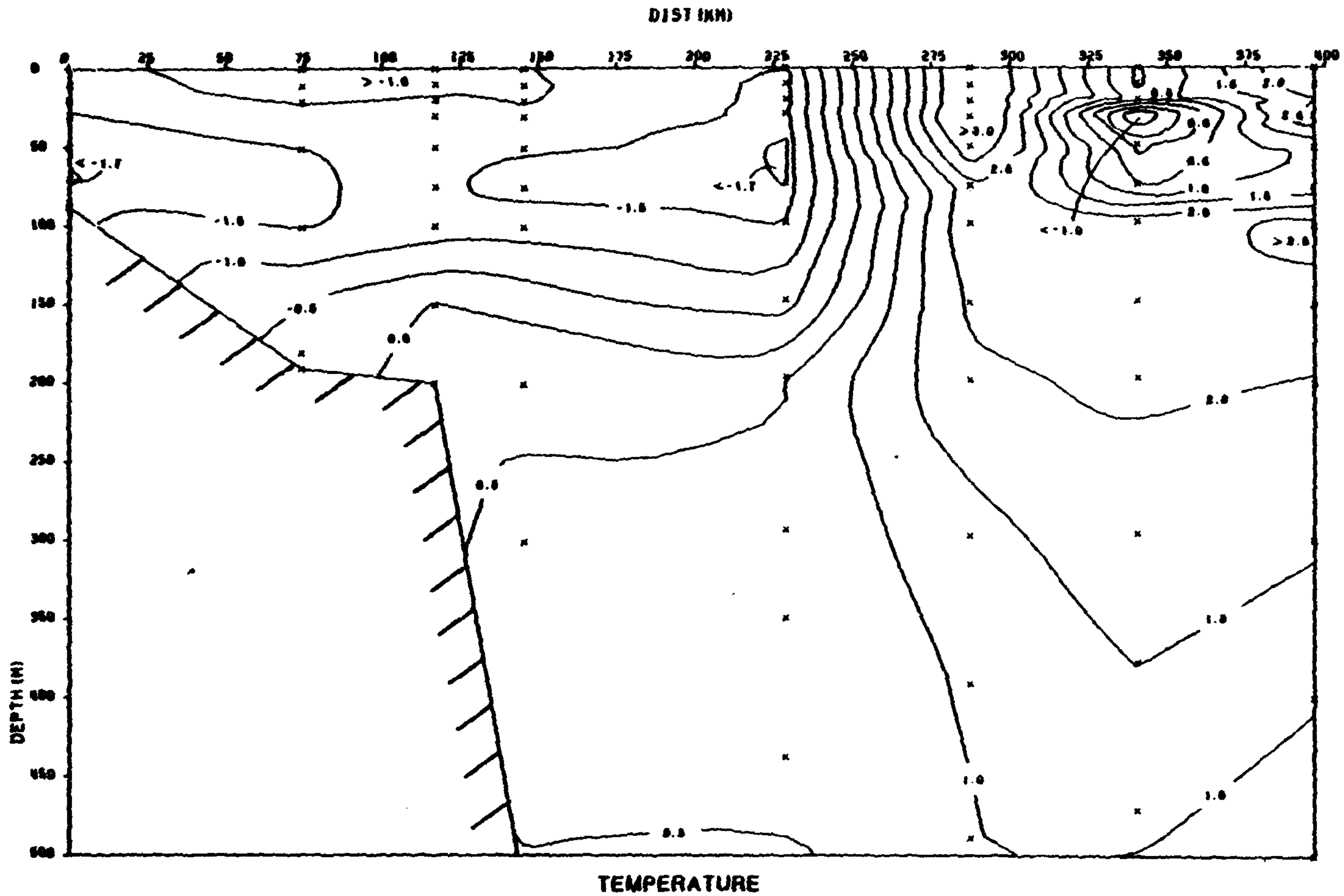

Figure 17. Transect B - Temperature (°C).

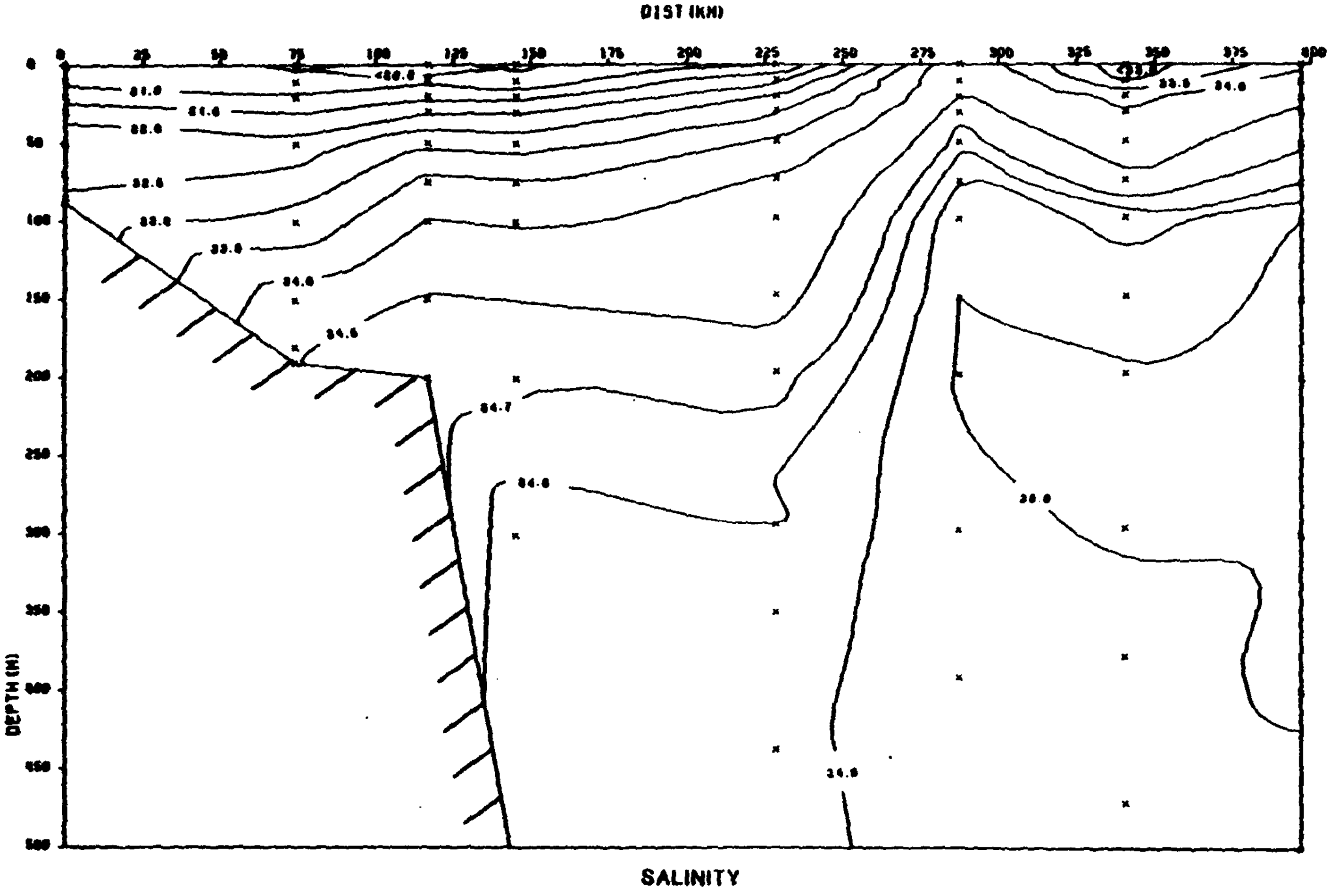

Figure 18. Transect 8 - Salinity (o/oo).

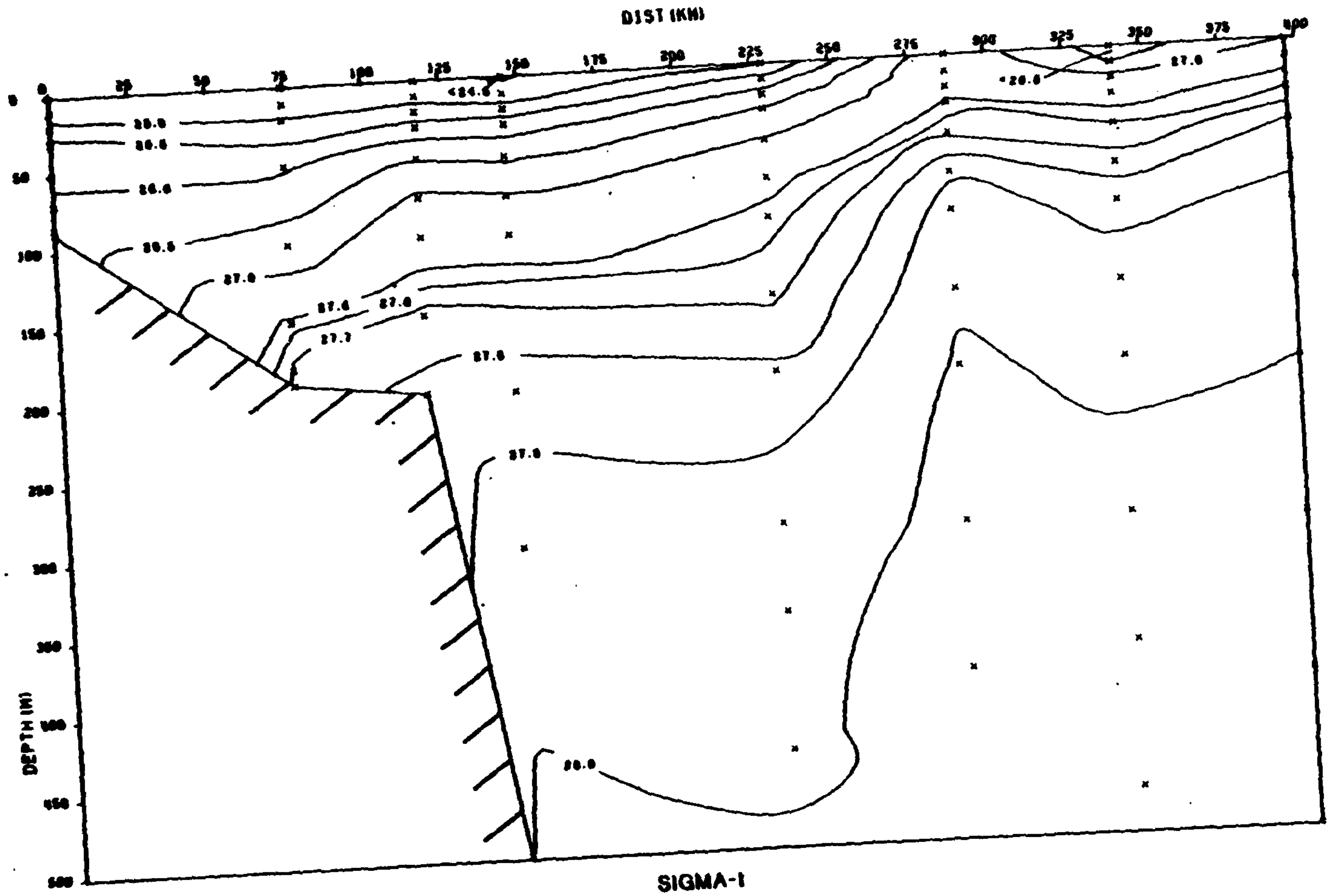

Figure 19. Transect B - Sigma-t ($kg\text{-}m^{-3}$).

(Figures 6-9). These parcels have been associated with the warm water seen on the continental shelf.

Any warm water above about 0°C an the shelf clearly has AIW as its source and it must have been injected not far upstream. The Arctic Ocean Intermediate Water, in its long counterclockwise circuit of the Arctic Ocean has cooled to a maximum temperature of about 0.4°C by the time it reaches the Beaufort Sea. If it were to continue around to Fram Strait, it would be cooled further. Thus, this classical Arctic Ocean Intermediate Water cannot account for the warm water; the warm intermediate water found on the Greenland Shelf must have been refreshed by AIW, either some distance north of Fram Strait or along the East Greenland Current or both. The tendency of the AIW to cross the front which has been described in the preceding paragraphs indicates that the second of these routes is not to be ignored.

It should be noted that the two southerly transects (Figures 8 and 9) are to a degree anomalous in that they are located opposite the mouth of Belgica Dyb into which there may be a circulation, as suggested by Newton and Piper (1981). While this circulation might accentuate the intrusion of AIW onto the shelf, it is evident from Transects 4 and 5 in the north that the tendency of the warm water to find its way up onto the shelf is present.

In the AIW, there is a great deal of inhomogeneity in both temperature and salinity which may well represent density anomalies which could be interpreted as eddies. In the more extreme cases, the density anomalies may be seen readily. In Transect 6 (Figure 14), the prominent dome in the isoterms at Station 81 was mentioned as suggestive of a cold-core eddy. Clearly, there is a marked decrease in the temperatures in the area with little compensating change in salinities, thus indicating a submerged region of elevated density and probable cyclonic eddy. In Transect 1 (Figure 8), there is a similar feature with a warm core located at Station 10, again in a region of low vertical salinity gradient; this implies an anti-cyclonic eddy. Still another eddy-like feature is visible at Station 30 of Cross Transect 2 (Figure 9). Among the many smaller features, it is not clear if any of these are also density anomalies or if there is compensation by concomitant salinity changes. A thorough discussion of the existence of eddies cannot be carried out without a study of densities and dynamic heights which are currently not available. This topic is left for later work.

V. SUMMARY

Examined in considerable detail with close station spacing and dense vertical sampling, the East Greenland Polar Front exhibits a wealth of structure and variability. The following major conclusions were drawn:

- Marked changes occurred in the front in the course of 8 to 10 days. Particularly notable was the distribution and fragmentation of the warm AIW core eastward and beneath the frontal zone.

- A core of warm Atlantic Intermediate Water is frequently found pressed against the eastward edge of the front. This core is warmer than previously described and is often fragmented and full of finestructure.

- There is finestructure of the order of 15m in thickness and 10km in diameter present in the Polar Water. Lenses of anomalous water, generally warm in a cold matrix, are widespread. The source of these warm parcels is AIW turbulently entrained at the front.

- AIW is the source of warm water on the Greenland Shelf; it has penetrated the lower portion of the front either some distance north of Fram Strait or along a part of the East Greenland Current or both. There is evidence that eddies or other mechanisms are involved in this process.

- An eastward extension of the near-surface isopleths of the front occurs with the prograding of the ice margin.

- The front is consistently associated with the upper continental slope, possibly due to bathymetric steering of the along front flow.

APPENDIX A

INSTRUMENTATION AND DATA ACQUISITION

Temperature and salinity profiles during the subject cruise were obtained utilizing a Neil Brown Instrument Systems (NBIS) Mark III conductivity-temperature-depth recorder (CTD). The conductivity cell was the standard 3 cm in length; the system was provided with a rapid-response thermometer stabilized by a platinum resistance thermometer and the pressure sensor had a range of 1600 dbar. The digital data stream was read into a Hewlett-Packard 9835-B computer which had enough memory to store about 3500 complete binary data records. The CTD was lowered at a rate of approximately 1 m/s; this slowed sampling rate resulted in a data record rate of about 3 points/m. To conserve cassete storage space and to allow flexibilty in cast depth, the computer was programed to also operate with 2625, 1750 or 875 memory records. Operating over the outer shelf and slope, 1750 records were most frequently used to reach depths of approximately 600m. In shallower regions on the shelf, 875 records were used, reaching about 300m. Before leaving each station, the data from both the downward and the upward profiles of the CTD were plotted on a 28x28 cm digital flat-bed plotter, Hewlett-Packard Model 9872A. Plot scaling could easily be changed to accomodate different depths and to expand scales when desired. This technique enabled the watch team taking the measurements to ensure that good, reliable data had been obtained. The plotted data also afforded the scientists an opportunity to alter the proposed course of action to investigate a particular area or phenomenon if desired.

The data were stored in their original binary form on a tape cassette, which is part of the computer. During the early phases of the cruise, only the downward traverse of the CTD was stored to ensure that no shortage of tape cassette supplies developed. Later in the cruise, this procedure was no longer necessary and both traverses were stored on the tape cassettes. Comparison of down and up profiles was particularly useful in quality control of the data. Following the cruise, the binary data stored on the cassette tapes were transferred to a 9-track computer tape at NPS for further editing and analysis.

Standardization of the CTD data was accomplished by comparison with temperature and salinity data taken by reversing thermometers and Nansen bottles. A total of 26 casts were made with a Nansen bottle 3 m above the CTD on the oceanographic cable. This placed the bottle in the largely isothermal and isohaline layer near the bottom of each cast. In the remaining 16 casts, the bottle was positioned near the surface in an isothermal, isohaline layer. By attaching the Nansen bottle to the cable and positioning it in such uniform layers, errors due to depth uncertainties and non-simultaneity between the Nansen bottle and the CTD were avoided. After removal of 10 faulty values, the temperature comparisons showed the CTD reading high by 0.004°C with a standard deviation of 0.013°C. Although this error is apparently significant, it was not applied. The salinity comparisons are based on only 17 samples (up to Station 51) compared directly with standard water, all but four vials of standard water having broken in transit. The mean showed the CTD high by 0.0056 o/oo with a standard deviation of 0.010 o/oo, again a significant error, but one which was not applied. The remaining samples were compared with a substandard which gave abruptly higher positive differences which drifted from about 0.03 o/oo to 0.103 o/oo by the end of the cruise. Although the direction of the drift was opposite to that expected, the substandard appearing to become more dilute, no faith was placed in the comparisons with substandard.

A total of 123 XBT drops were made. For purposes of this thesis, only 7 of these have been used to supplement CTD data.

Positioning was accomplished primarily by the use of information obtained from a Magnavox MX 1107 Satellite Navigation System. The system worked well throughout the cruise, providing an average of 28 reliable fixes each day. NAVSAT fixes often occurred during or close to the time of CTD casts, resulting in excellent station position accuracy, probably within 1/2 nautical mile.

APPENDIX B

CTD OPERATIONS UNDER FREEZING CONDITIONS

Bourke and Paquette (1981) have documented the difficulties involved in the operation of a CTD in ice under freezing condidtions. The benefit of this prior experience enabled relatively smooth operations during most of the present cruise. One problem of significance which was not satisfactorly solved was related to the on deck storage of the CTD.

Once air temperatures drop below -1.8°C, the underwater unit if left on deck in the cold, would freeze water in the conductivity cell and in the port of the pressure transducer. Since air temperatures during most of the cruise rarely exceeded -5°C, this problem required constant monitoring. a box cosisting of canvas stretched over a wooden frame was used to cover the CTD between casts. A hose with low pressure steam was placed under the box to help keep the sensors warm. As a further precaution, the instrument was soaked and moved up and down in the water several times just prior to each cast to remove any remaining ice film. These efforts proved adequate as long as temperatures remained in the -5°C range. However, when air temperatures dropped to -15°C, the steam supply could no longer maintain enough heat inside the box and ice formed on the sensors from condensing steam. To aid in the remcval of this fresh water ice, it was necessary to flush the sensors with warm salt water immediately prior to lowering in addition to the soaking procedure. Replacing the steam hose with heat lamps and adding a additonal layer of canvas to the box helped to reduce the freezing problem, however it was necessary to take care that the instrument was not allowed to overheat.

Future cruises conducted under feezing conditions probably should employ a seawater bath. Such a system would be quite simple in construction. It would consist of bucket or tub in which the CTD could be immersed in salt water between casts. The tub could be insulated and provide for a constant supply of water, lcw energy electric heat or steam. it would also be necessary to construct a frame with some type of block and tackle system to aid in hoisting the instrument in and out of the salt water bath. This system should eliminate the need for application of heat directly to the instrument, and it should avoid the formation of ice on the sensors.

APPENDIX C

CHARTS OF ARCTIC SOUTHERN ICE LIMIT

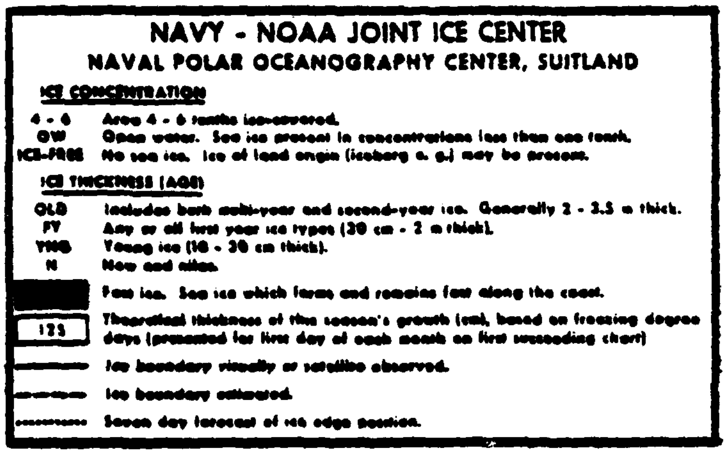

Figure 20. Southern Ice Limit Chart Legend.

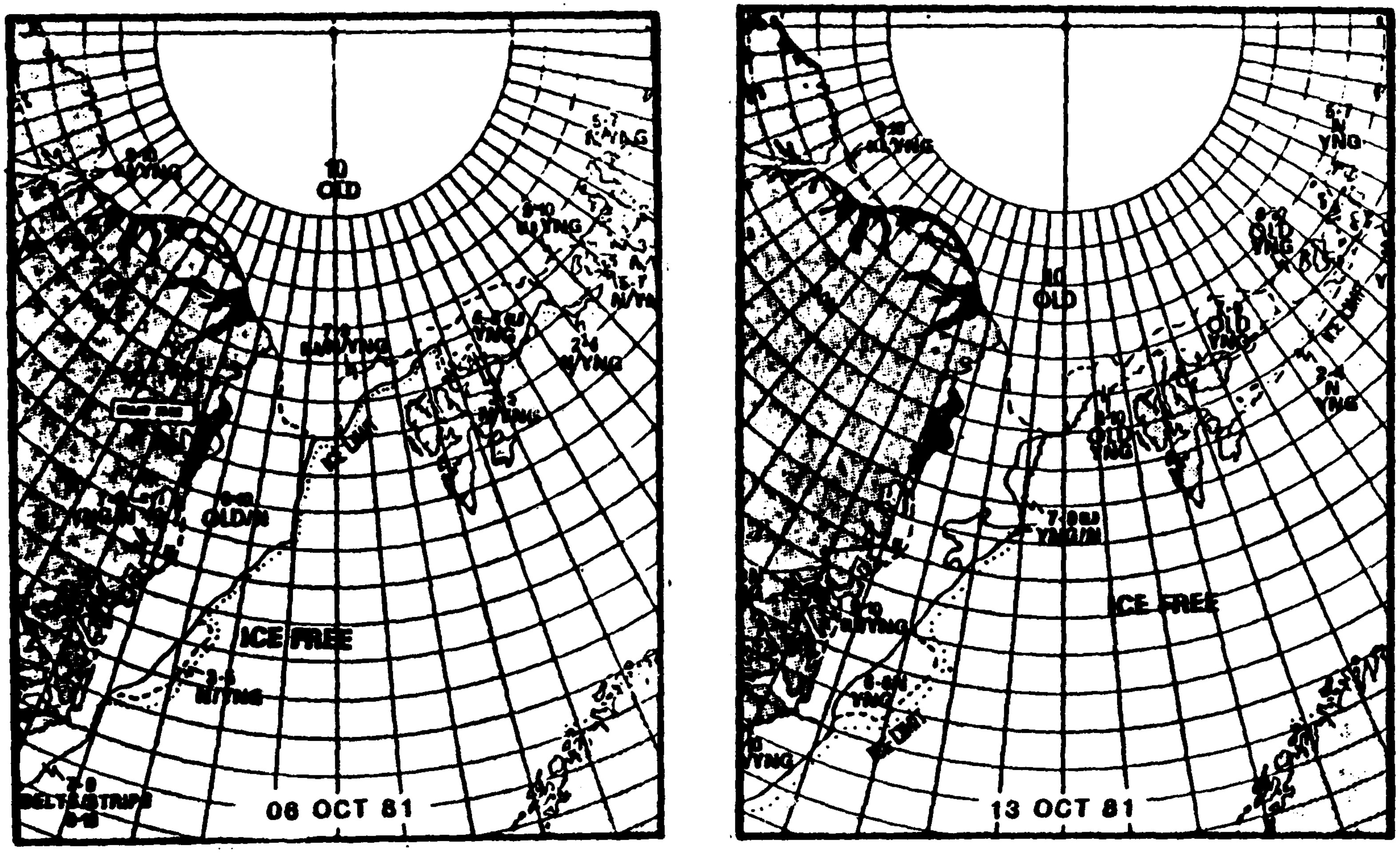

Figure 21. Southern ice limit - 6 and 13 October.

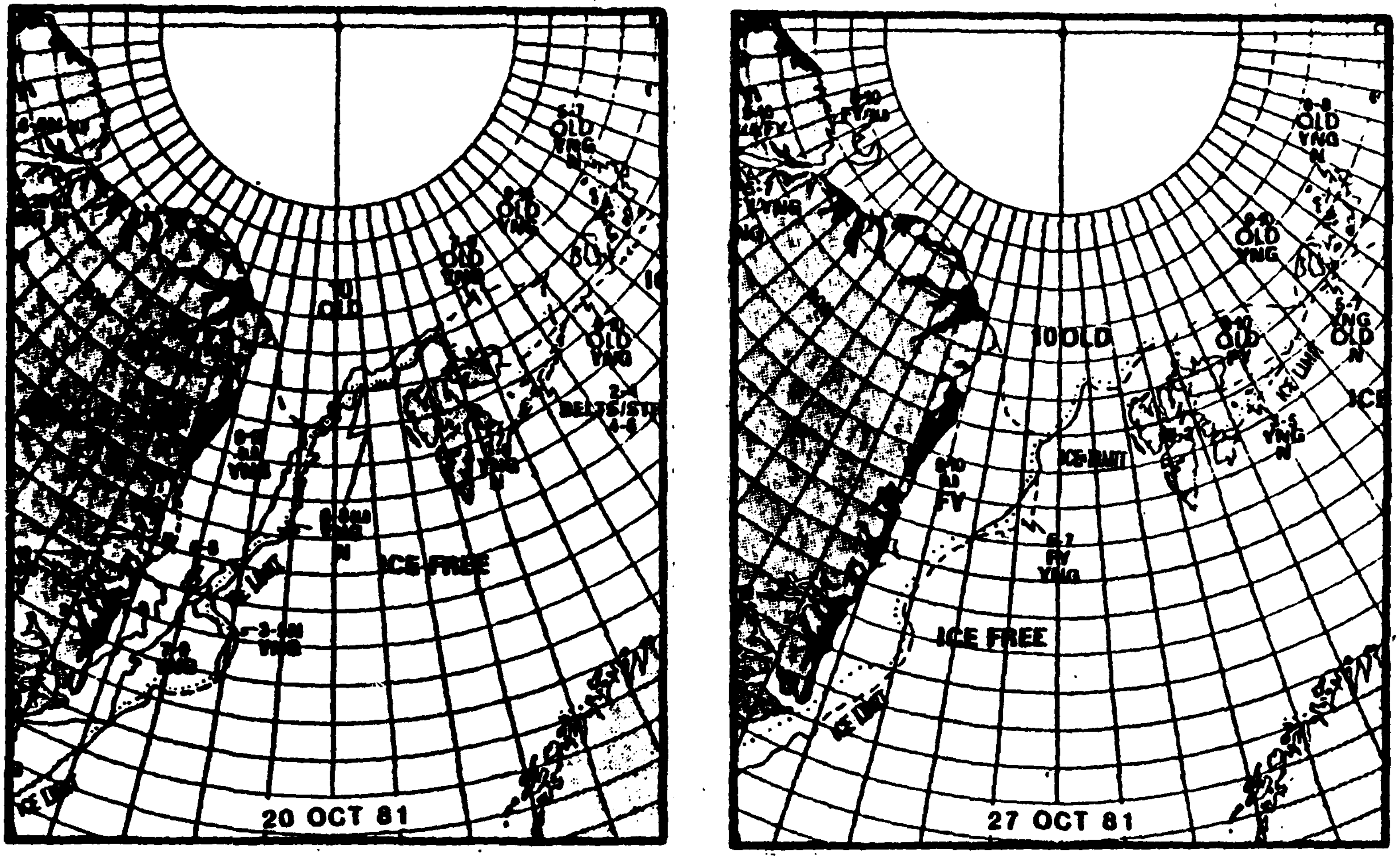

Figure 22. Southern ice limit - 20 and 27 October.

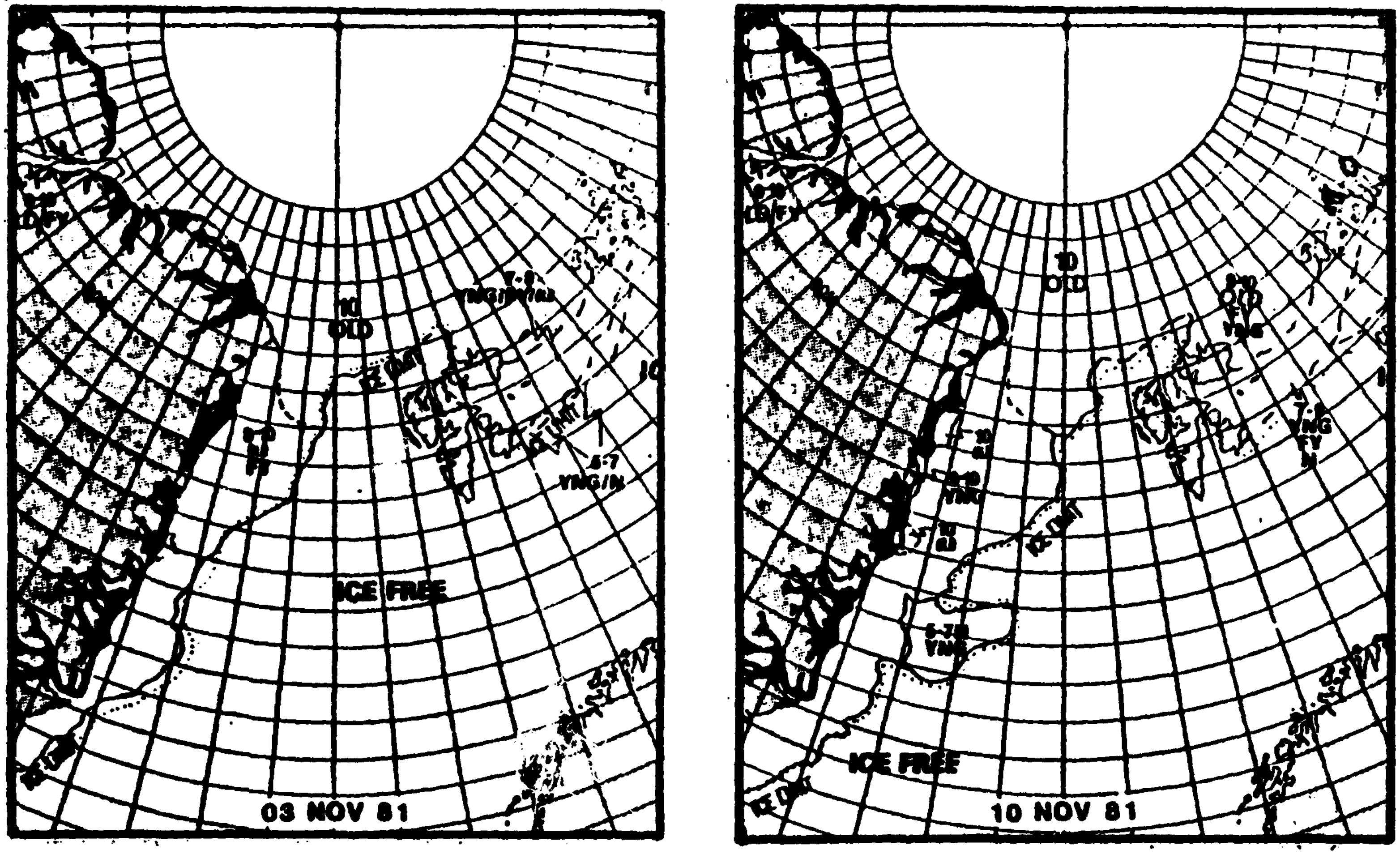

Figure 23. Southern ice limit - 3 and 10 November.

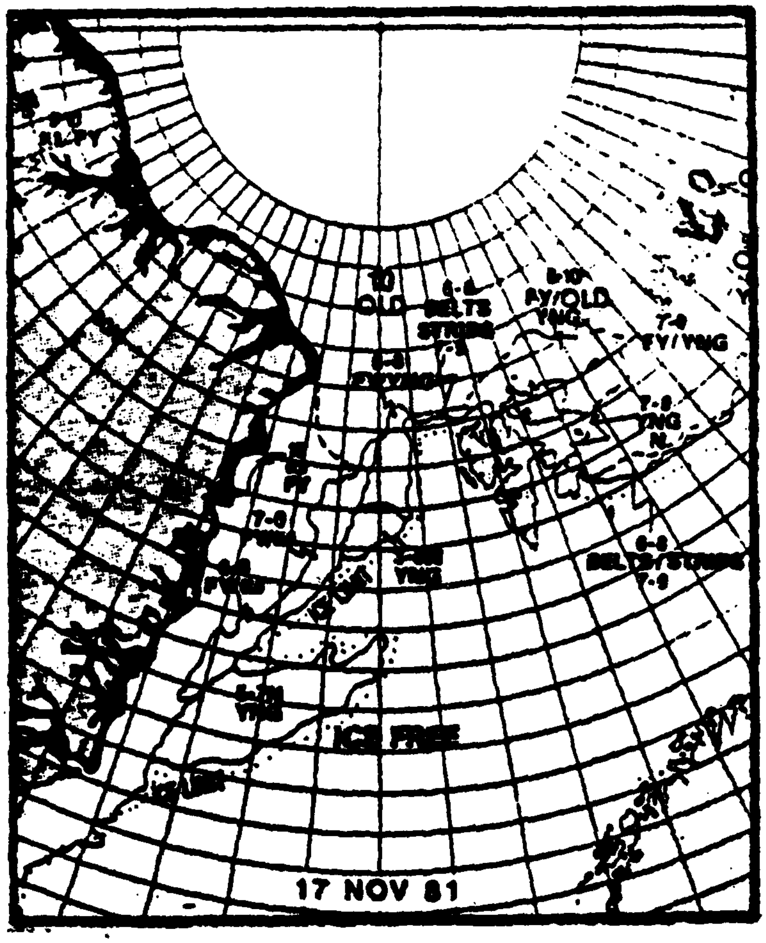

Figure 24. Southern ice limit - 17 November.

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